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Danksagung

Zu allererst möchte ich Professor Michael P. Wistuba für seine umfangreiche Unterstützung bei meiner Arbeit am Institut danken. Durch seine freundschaftliche und unkomplizierte Art war er für mich ein hervorragender Wegbegleiter. Ohne seine fachliche Kompetenz wäre die Erarbeitung der Lösungen innerhalb meiner Dissertation deutlich erschwert gewesen.

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Ich danke herzlich allen Kolleginnen und Kollegen des ISBS für die großartige Unterstützung beim Erlernen der deutschen Sprache, sowie für die umfangreiche Motivation und für den fachlichen Austausch.

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Zu guter Letzt bin ich meiner Familie für das bedingungslose Vertrauen in mich überaus dankbar.

Vorwort des Herausgebers

Dieses Heft ist die kumulative Promotionsschrift von Dr.-Ing. Ivan Isailović, M.Sc. Die Arbeit ist der experimentellen Analyse des Verhaltens von Asphalt unter zyklischer Dauerbelastung gewidmet. Sie besteht aus 2 Teilen. Der erste Teil bildet die inhaltliche Klammer, der zweite Teil enthält 7 Publikationen: 6 reviewte Journalbeiträge und ein reviewtes Konferenzpaper, alle in englischer Sprache. Ivan Isailović ist bei allen Publikationen, die in Kooperationen mit unterschiedlichen Mitautoren entstanden sind, der Erstautor. In der ersten Publikation (A) vergleicht er mit Hilfe der Auswertung der während des Versuchs dissipierten Energie den in Deutschland weit verbreiteten Spaltzug-Schwellversuch mit anderen Laborversuchen zur Ermüdungsprüfung und liefert damit wichtige Erkenntnisse zur Wahl der Prüfmethodik. In der zweiten Publikation (B) beleuchtet er das Problem der normgemäßen Analyse des Ermüdungsverhaltens bei einer einzigen Prüftemperatur und schlägt ein neues Prüfverfahren vor, mit dem unter Ausführung eines Amplitudensweeps das Ermüdungsverhalten über den gesamten Gebrauchstemperaturbereich analysiert werden kann. Mit den Publikationen C, D und E trägt Ivan Isailović bei zur Entschlüsselung des Heilungsverhaltens von Asphalt, also dem Vermögen, einen während des Ermüdungsversuchs beobachteten Steifigkeitsverlust durch Einführung von Lastpausen wieder zurückzustellen. In der Publikation C analysiert er die Einflussgrößen unterschiedlicher Prüfvariablen (Bindemittelgehalt, Verdichtungsgrad, Lastpausendauer, Alterungszustand, Bindemittelsorte) auf die Heilungs-Eigenschaften, in Publikation D entwickelt er einen neuen Index zur vergleichenden Bewertung des Heilungsvermögens, der den Vorteil hat, dass die materialbedingte Streuung im Prüfergebnis reduziert ist. Schließlich isoliert er die Nebeneffekte aus Nichtlinearität und Selbsterwärmung von der eigentlichen Materialheilung und stellt fest, dass der Effekt der Nichtlinearität einen relativ geringen Einfluss auf die Heilungs-Eigenschaften hat und unabhängig ist von der Lastpausendauer, während im Gegensatz dazu der Selbsterwärmungseffekt einen signifikanten Einfluss hat (Publikation E). Mit der Publikation F entwickelt Ivan Isailović den bekannten zyklischen Schersteifigkeitsversuch zur Analyse des Schichtenverbundes weiter zu einer neuen Scherermüdungsprüfung, analysiert die Einflüsse aus Prüftemperatur, Normalspannung und materialspezifischen Parametern und schlägt Prüfparameter vor, mit denen eine bestmögliche Ermüdungsbewertung des Schichtenverbundes erfolgen kann. In der Publikation G vergleicht er Ergebnisse aus zyklischen und monotonen Scherversuchen und stellt fest, dass eine nur schwache Korrelation zum monotonen Scherversuch formuliert werden kann und die resultierende Scherkraft aus dem monotonen Scherversuch als ein nur grober Indikator für die Bestimmung der Lebensdauer des Schichtenverbundes herangezogen werden kann.

Mit dieser Arbeit hat Dr.-Ing. Ivan Isailović, M.Sc. im Frühjahr 2018 sein Promotionsstudium an der Fakultät für Architektur, Bauingenieurwesen und Umweltwissenschaften der Technischen Universität Braunschweig mit Auszeichnung abgeschlossen. Ich gratuliere ihm dazu ganz herzlich und freue mich, die Promotionsschrift im Rahmen der Schriftenreihe des ISBS herausgeben zu dürfen.

Braunschweig, im August 2018

Michael P. Wistuba

Contents

Contents of this thesis

Fatigue is a key failure mode of asphalt pavement structures. Stress in consequence of repeated traffic loading and temperature changes may significantly weaken the coherence of the asphalt mixture with time. This long-term deterioration mechanism is generally called "fatigue", usually understood as the formation of a micro-crack network weakening strength of the asphalt pavement.

As pavement structures are not continuously loaded, and because asphalt is a highly viscous material, already developed micro-cracks may close during non-loading phases partially or even entirely in consequence of viscous flow. Thus, an intermediate "recovery" of strength loss may take place.

This thesis is devoted to the investigation of both fatigue and recovery properties of asphalt materials. It is structured to five main Chapters. The first two Chapters are dedicated to a general introduction to fatigue and recovery properties of asphalt in-situ (Chapter 1) and in laboratory (Chapter 2). The terms "fatigue" and "recovery" are well defined, and the fatigue and recovery performance mechanisms of the asphalt material as well as fatigue of the interface of two asphalt pavement layers are described. The third Chapter outlines the research work, giving a motivation and a comprehensive summary. The forth Chapter is composed of a number of contributions to high-level peer-reviewed international journals in the domain of material science. The first two publications are dealing with fatigue evaluation of asphalt mixtures; third, fourth, and fifth publications are devoted to evaluation of asphalt mixture recovery properties; sixth and seventh publications are focused on fatigue evaluation of asphalt mixture layers' interface.

The first publication (A) "*Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests*" is dedicated to an appropriate evaluation of asphalt mixture fatigue properties in laboratory. Since several test types are available, and even though a number of which is also described in technical guidelines, there is no consensus between researchers about the most appropriate test method for determining the asphalt mixture fatigue resistance. This thesis provides new insights into various techniques of laboratory fatigue evaluation, and assists in selecting most appropriate method for testing and data analysis. For stress controlled testing mode, the uniaxial tension-compression test is identified as most reliable for evaluating asphalt fatigue properties and recovery capacity.

The second publication (B) "*Sweep test protocol for fatigue evaluation of asphalt mixtures*" focuses on investigating the temperature dependency of asphalt fatigue. Asphalt mixture fatigue properties determined by means of fatigue function at a single test temperature, although in best accordance with the European Standard (EN 12697-24, 2012), is not representative for the whole in-service-temperature range. Therefore, fatigue tests which are limited to a single temperature may provoke misleading conclusions, especially for modified asphalt mixtures, where little or no experience exists about their long-term behaviour in-situ. In order to overcome any potential shortcomings if studying the asphalt mixture fatigue resistance according to European Standard, a new test protocol is introduced, which allows for plausible evaluation of asphalt mixture fatigue performance considering a wide temperature range. The new test protocol relies on amplitude sweep test, with a marginally increased laboratory effort if compared to the procedure at single test temperature according to the European Standard.

The third publication (C) "*Investigation on mixture recovery properties in fatigue tests*" aims in clarifying the dubiety about the factors influencing asphalt mixture recovery potential. Due to the application of different materials and test methods, some influencing parameters are not well assessed, because of either contradictory or non-plausible test results, e.g. the effects of bitumen polymer modification, ageing condition. Therefore, beside effects of ageing and bitumen polymer modification, further effects influencing asphalt mixture recovery properties are investigated, such as asphalt binder content, degree of compaction, and rest period duration. It was found that the asphalt ageing condition seems to be the most influencing parameter regarding asphalt mixture recovery potential.

The forth publication (D) "*Experimental study on asphalt mixture recovery*" focuses on improving the laboratory evaluation of asphalt mixture recovery properties. Due to the potentially large scattering of the experimental results observed in cyclic tests, the commonly used recovery index, relying on fatigue live comparison of tests with and without rest period, may lead to the erroneous evaluation of the recovery potential. In order to allow an accurate evaluation of the asphalt mixture recovery potential, a new recovery index is developed, which can substantially and successfully mitigate the material-related scatter observed in the experimental tests without rest period. The procedure relies on a normalized energy ratio-complex modulus curve that shows a unique trend for all tests conducted at the same loading conditions.

The fifth publication (E) "*Influence of rest period on asphalt recovery considering nonlinearity and self-heating*" is dedicated to a detailed investigation of asphalt mixture recovery potential, taking into consideration biasing effects such as nonlinearity and self-heating observed during cyclic loading. These effects are barely investigated in tests in stress controlled mode, and their contribution to the recovery of asphalt mixture mechanical properties with the change of rest period duration is unclear. Based on stress controlled discontinuous fatigue tests with single rest periods of different durations, it was found that the effect of nonlinearity on complex modulus recovery is relatively small and it is not affected by increasing duration of the rest period. Contrary, the self-heating effect has a significant influence on asphalt mixture recovery properties. It results in a much more rapid recovery of complex modulus than other eventual side effects, such as thixotropy, self-healing, and strain relaxation.

The sixth publication (F) “*Fatigue investigation on asphalt mixture layers' interface*” focuses on investigating the fatigue performance mechanisms of the interface of two asphalt pavement layers, and on characterizing the influence of material and test related factors on fatigue performance. Using a set of bond types differing in the asphalt mixture types, tack coat types, and tack coat application rates, it was found that the interface shear fatigue performance is highly dependent on normal stress state and increases with increasing normal stress. This is a direct consequence of the enhanced friction, adhesion and interlock at the shear interface. Observing the layers' interface fatigue resistance at different test temperatures, the best results were observed at the lowest temperature. Based on this preliminary work, the test parameters are proposed, allowing for a successful fatigue evaluation of layers' interfaces.

The seventh publication (G) “*Asphalt mixture layers' interface bonding properties under monotonic and cyclic loading*” focuses on clarifying the question, if the outcomes from monotonic shear tests are comparable with outcomes from fatigue shear tests. Based on the research results obtained from a set of bond types, it was found that the resulting shear strength from monotonic shear test can be used only as a rough indicator for long term interface bonding performance, because not all research and field experience could be reflected in the test results. The differences in bond types with some specific material and production variations cannot be recognized as good as when using the cyclic fatigue shear test.

1 Definition of terms – Fatigue and recovery in the context of asphalt materials

In principal, asphalt mixtures used for flexible pavements are composed of aggregate and bitumen. Bitumen derivates from refinery process of petroleum, which composition is primarily driven by the cocktail of hydrocarbons originating from the crude oil. While the aggregates structure provides the majority of compressive load resistance, the bitumen serves to glue the aggregates together and to give asphalt mixture the resistance to tensile stresses (Johnson, 2010). Additionally, bitumen contributes to the waterproofing characteristic of asphalt that protects underlying foundation unbound aggregate layers that are typically susceptible to reduction in modulus with addition of moisture. Due to the specific rheological properties of bitumen, asphalt mixture is generally considered as a visco-elastic material, showing high temperature dependency.

Flexible pavements consist of several asphalt layers which are built successively. The main structural function of these layers is to support and withstand traffic and temperature stresses and to distribute them to the underlying subgrade. Therefore, according to the available empirical and mechanistic-empirical pavement designs, asphalt mixtures have to be appropriately conceived in order to serve for the defined lifespan.

It is generally agreed that fatigue cracking, rutting and low temperature cracking (see Figure 1) are three principal types of distress to be considered for the design of asphalt mixtures and for asphalt pavement design (Huang, 2004). Among them fatigue cracking represents the primary failure mode in asphalt pavements (Hintz, 2012).

In association with fatigue cracking in flexible pavements, the following phenomena are distinguished: fatigue of asphalt layer materials, recovery of asphalt layer materials, and fatigue of interface bonding between asphalt pavement layers.

Figure 1. Fatigue cracking (left), rutting (middle) and low temperature cracking (right) as common distresses considered for flexible pavements.

1.1 Fatigue of asphalt materials

In materials science, fatigue refers to the behaviour of materials under the action of repeated stresses or strains, as distinguished from their behaviour under monotonic load (Stephens et al., 2001). According to the ASTM (2013) material fatigue is defined as follows:

"*The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations*".

The term progressive implies that the fatigue process occurs over a period of time or usage (Stephens et al., 2001). The structural change during fatigue process is localized, because fatigue process operates at local areas rather than throughout the entire component or structure. These local areas can have high stresses and strains due to external load transfer, abrupt changes in geometry, temperature differentials, residual stresses, and material imperfections. The term permanent implies that once there is a structural change due to fatigue, the process is irreversible. Process of fatigue involves fluctuating stresses and strains that are cyclic in nature and requires more than just a sustained load. Even though the individual load is lower than the material's ultimate strength, the repetition of loads may induce damage of the material after many loading cycles. Fatigue process results in structural cracking that with repeated loading leads to the complete structural fracture.

Considering the asphalt materials used for flexible pavements, similar fatigue definition is widely accepted. Due to the visco-elastic properties of asphalt mixtures, there is a possibility of reversible fatigue process (recovery) that represents the solely deviation to the abovementioned fatigue definition.

In asphalt mixtures, fatigue results in material cracking initiated by repeated traffic load. During fatigue cracking in asphalt mixtures, two phases of the degradation process are usually considered; initiation phase and propagation phase (Di Benedetto et al., 2004). The first phase is manifested by the initiation of micro-cracks that usually develop at a point of localized stress concentration like discontinuity in the material. Once a micro-crack is initiated, the stress concentration effect increases and micro-crack propagates. This results in a decrease in the macroscopic asphalt rigidity. In the second phase, from the coalescence of micro-cracks, a macro-crack appears which propagates within the material (see Figure 2). Consequently the stressed area decreases in size, the stress increases in magnitude and the crack propagates more rapidly. Until finally, the remaining area is unable to sustain the load and the material fractures. This can significantly affect the pavement bearing capacity and durability. Additionally, reduced ride comfort is expected (Johnson, 2010).

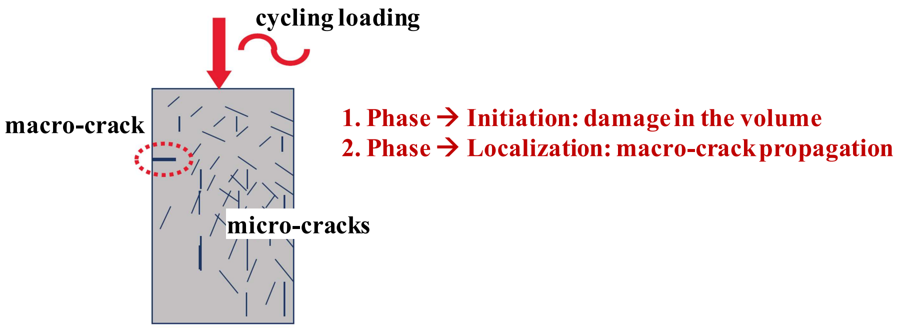


Figure 2. Two phases of the degradation process during fatigue cracking (acc. to Di Benedetto, 2013).

Two mechanisms of fatigue cracking in asphalt pavements are recognized in-situ: top-down and bottom-up (Huang, 2004).

Top-down cracks initiate at the top (surface) layer as a result of the repeated transversal tensile strain near the edge of the tire (Molenaar, 2007). This type of distress manifests in longitudinal cracks that propagate downward (Hintz, 2012). Top-down cracking is particularly pronounced in cold climates, where traffic bending transversal stresses are superimposed with cryogenic stresses due to decreasing pavement temperature and restrained thermal contraction of asphalt mixture (cp. Arand, 1985).

The bottom-up cracking mechanism is seen as the most common form of fatigue cracking that is usually considered as the main failure mode for pavement design. Bottom-up cracks initiate at the bottom of an asphalt base layer as a result of high strains associated with flexure (Hintz, 2012). Figure 3 (left) shows the evolution of horizontal strains measured at the bottom of asphalt base layer subjected to loading by different vehicle axles. The dominating horizontal tensile strain (see Figure 3) leads under the effect of repeated loading to cracking (damage), which propagates upward and induces an inter-connected network of cracks often referred to as alligator cracking at pavement surface (see Figure 1, left).

Nevertheless, both bottom-up and top-down cracking mechanisms should be equally considered, since in some cases, top-down cracking might be dominant over bottom-up cracking (Molenaar, 2007).

In this thesis, the investigation of asphalt mixture fatigue resistance is topic of the Publications A and B (see Section 4).

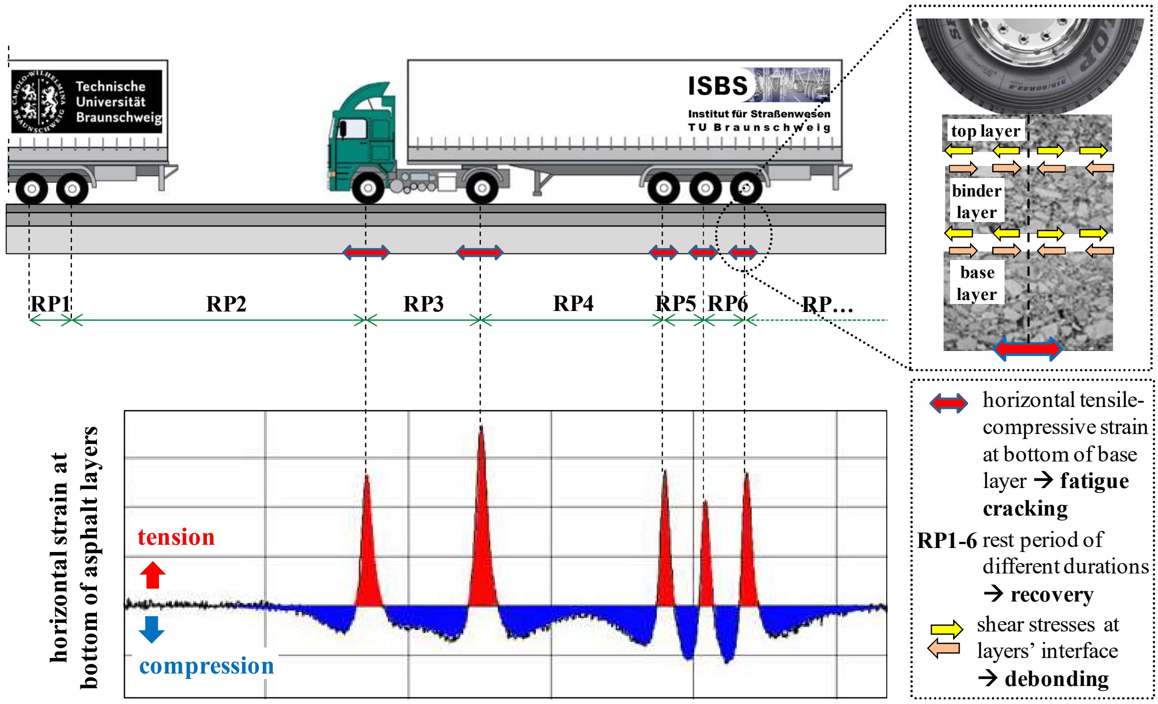


Figure 3. Evolution of horizontal strains measured at the bottom of asphalt base layer subjected to loading by different vehicle axles (left) (strain measurements acc. to Rabe, 2008); detail on the shear stresses at layers' interfaces (right).

1.2 Recovery of asphalt materials

Recovery (or self-healing) effect is defined in material science as an opposite process to fatigue cracking (Luo, 2013). Self-healing materials are able to counter degradation through the initiation of a repair mechanism that responds to the micro-damage (Ghosh, 2008). For a material to be strictly defined as autonomously self-healing, it is necessary that the healing process occurs without external intervention. Only few materials exhibit these properties such as polymers, metals, ceramics, glass, cementitious materials, bitumen (Wool, 2008; Qiu, 2012; Shen and Carpenter, 2007).

Since bitumen represents the substantial part of asphalt mixtures and dominates their rheological and mechanical properties, asphalt mixture is generally considered as a self-healing capable material. In civil engineering, self-healing of asphalt mixtures is defined as the intrinsic response of bitumen to diminish the generated cracks within the bituminous body under certain loading and environmental conditions (Shen and Carpenter, 2007; Ayar et al., 2016).

Self-healing usually occurs in pavements during the rest period between repeated axle loads of the same or of different vehicles (cp. rest periods RP1-RP6, Figure 3, left). Nevertheless, some researchers observed that the recovery process can occur during traffic loading too, and not only during rest periods (Soltani and Anderson, 2005; Ashouri, 2014). The self-healing capability of asphalt mixtures is limited to the repair of micro-cracks, since macro-cracks do not close unless external forces are applied to press the cracked surfaces together (Jones and Dutta, 2010). Depending on the crack intensity, partial or full recovery of the mechanical properties is possible.

The self-healing mechanism of asphalt mixtures is reversed to fatigue cracking and can be described using a three step model: i) flow, ii) wetting, and iii) diffusion (cp. Figure 4, Phillips, 1998). The first step implies the crack surface approach due to the consolidation of stresses and flow of bitumen. In the second step, contact and adhesion are established between two crack surfaces by the surface energy driven wetting process. Wetting ability is related to the type of bitumen, and increases with increased bitumen's surface energy (Ashouri, 2014). In the last step, the complete recovery of mechanical properties happens due to diffusion and randomization of asphaltene structures. The diffusion capability is directly related to mobility potential of the molecules in the bitumen.

Step (i) is believed to be the fastest, resulting only in the recovery of stiffness, while steps (ii) and (iii) are thought to occur much slower but to improve both stiffness and strength of the material such that it exhibits mechanical properties similar to the virgin material (Qiu, 2012).

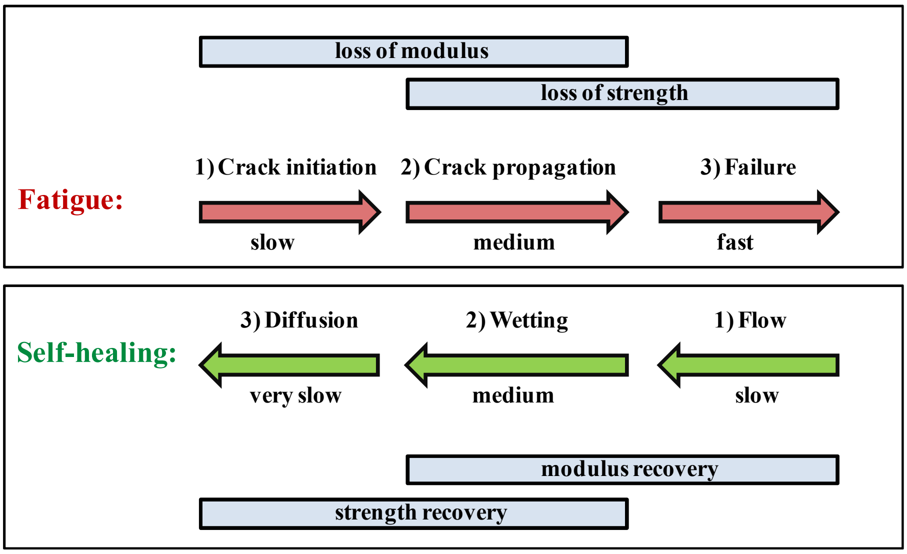


Figure 4. Multi-step fatigue and self-healing model (acc. to Phillips, 1998).

Generally, it is believed that during the service life of asphalt pavements, there is a steady competition between fatigue and self-healing (Phillips, 1998). Self-healing potential can extend the durability of asphalt pavements, since asphalt materials with high recovery capability accumulate less deformation and less damage in the asphalt layers (Luo et al., 2013). Therefore, such a property should be considered during materials selection and pavement design (cf. Di Benedetto et al., 2004, 2011; Santagata et al., 2013).

In this thesis, the investigation of asphalt mixture recovery properties is topic of the Publications C, D, and E (see Section 4).

1.3 Fatigue of interface bonding between asphalt pavement layers

Flexible pavement consists of several asphalt layers which are built successively. In order to ensure an appropriate bonding between them, the surface of the existing layer is usually cleaned and covered with a thin layer of a bituminous tack coat material before paving the next asphalt layer. The bond between these layers is achieved by the interaction of adhesion, friction and interlocking effects at the layers' boundary (Wistuba et al., 2016), and should ensure that those layers work together as a composite structure to withstand traffic and environmental loadings (Sutanto, 2009).

Although two asphalt layers are connected by means of a thin layer of tack coat material, the interaction between these layers may be insufficient to prevent relative displacement between them during traffic loading (cp. Tozzo et al., 2014). In consequence, traffic induced repeated shear stresses/displacements at the layers' interface (see Figure 3, right) can lead to fatigue cracking between asphalt layers. Finally, interface failure and a complete separation (debonding) of pavement layers may happen.

Shear stresses/displacements are initiated due to the simple action of rolling wheel loads and particularly increase during braking, accelerating and turning wheel phenomena (Romanoschi and Metcalf, 2001). According to Sutanto (2009), interface failure mechanisms can be categorized by the following separation modes (Figure 5): shear, tensile, and mixed shear-tensile mode. The shear separation mode (see Figure 5, a) occur in the transverse or longitudinal direction and is typically generated by traffic and/or temperature induced shear stresses at the interface. This mode of failure is frequently observed in the field and is mainly associated with the effect of interface fatigue. Tensile separation mode (see Figure 5, b) occurs as a result of blistering, and may be also initiated by the vertical tensile stress due to the suction process of tires. A mixed shear-tensile separation (see Figure 5, c) can arise at the interface beneath a thin surfacing layer, caused by the bucking of surface layer in front of the tire (cp. Sutanto, 2009).

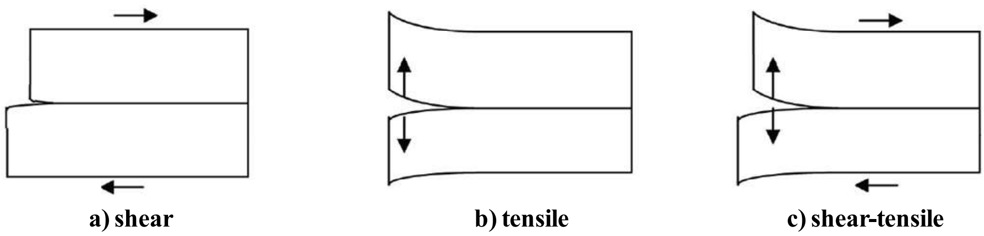


Figure 5. Separation modes of asphalt layers: a) shear, b) tensile, and c) shear and tensile (Sutanto, 2009).

Slippage cracking and permanent deformations are the most typical distresses associated with debonding (Tozzo et al., 2014). Furthermore, if the transfer of shear stresses at the layers' interface is not provided (due to debonding), the pavement cannot act as a whole structural unit. This may result in a serious change of the three-dimensional stress state in the entire structure, leading to significant increase in tension stresses at the bottom of the asphalt base layer (Wistuba et al., 2016). Consequently, bottom-up cracking is accelerated and an essential reduction of the structural bearing capacity and thus a much shorter service life is expected. According to the analytical analysis performed by Kruntcheva et al. (2005) it was shown that in case of a complete debonding of asphalt layers, the reduction of pavement life can reach 80 %. The importance of good bonding and accordingly good transfer of stresses in multilayered pavements was illustrated by the simple example from Weber (1991), where the deflections of beams with full bonding and without bonding are compared. Based on linear elastic bending theory, a nine-fold increase in the deflection of a three-layer beam without bonding (see Figure 6, right) is observed if compared to beams with full bonding (see Figure 6, left).

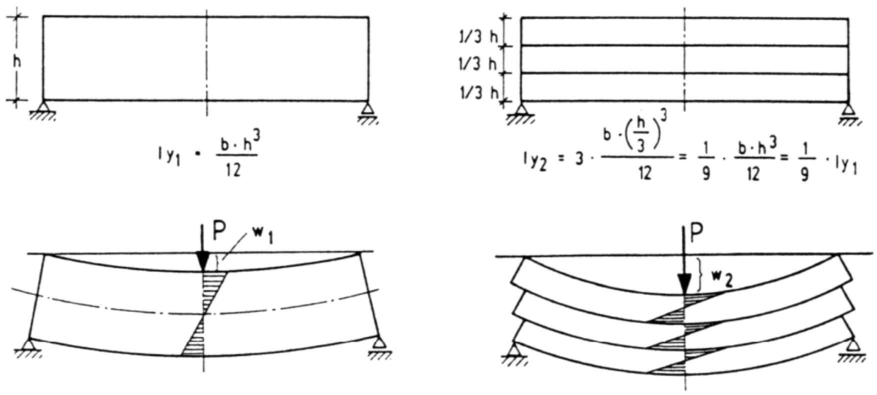


Figure 6. Evolution of horizontal stress in different layer systems with equal thickness, observed under application of force P: full bonding between layers (left), and missing bonding between layers (right) (Weber, 1991).

In this thesis, the fatigue investigation on asphalt mixture layers' interface is topic of the Publications F and G (see Section 4).

2 State-of-the-art report on laboratory test methods to identify fatigue and recovery properties of asphalt materials

2.1 Fatigue testing of asphalt mixtures

Asphalt mixtures for flexible pavements are designed to withstand traffic and temperature stresses in the long term. Suitability of a particular asphalt mixture can be assessed in laboratory by applying performance-oriented test methods to address the essential material properties such as stiffness, fatigue resistance, resistance to low-temperature cracking, and resistance to permanent deformation (rutting).

Conventional laboratory test methods for characterizing the asphalt mixture fatigue resistance do not simulate the traffic loading in-situ exactly, since the inclusion of rest periods in the test procedure would imply long tests durations, which may not be practical on a routine basis. Therefore, fatigue resistance of asphalt mixtures is studied using cyclic tests, where sinusoidal continuous loading is applied on asphalt mixture specimen, produced either in laboratory or cored from the field (Di Benedetto et al., 2004). Due to the visco-elastic rheological properties of asphalt mixture, the cyclic behaviour is usually characterized by means of complex modulus and dissipated energy, as detailed in the following.

a) Complex modulus

If a sinusoidal force/stress (see Figure 7, left) with the cyclic frequency $f = \omega/2\pi$ is applied to the visco-elastic material such as asphalt mixture, this will induce a sinusoidal response in the asphalt specimen. The resulting strain $\varepsilon(t)$, measured on the surface of the asphalt specimen using e.g. linear variable strain transducers (LVDT) will lag behind by the phase angle ϕ due to the visco-elastic material property (see Figure 7, left). The phase angle ϕ is also referred to as the loss angle (e.g., used to estimate the energy dissipated in the material during cyclic loading), and is a function of the internal friction of the material (Findley et al., 1976). For visco-elastic materials the phase lag is always $0 \leq \phi \leq \pi/2$, where $\phi = 0$ for elastic behaviour, and $\phi = \pi/2$ for viscous behaviour.

The complex modulus E^* of an asphalt mixture is a complex number defined as the ratio between the sinusoidal stress and the sinusoidal strain (see Figure 7, middle), reading

$$
\begin{aligned}
E^*(\omega) &= \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma_0 \cdot \cos(\omega \cdot t) + i \cdot \sigma_0 \cdot \sin(\omega \cdot t)}{\varepsilon_0 \cdot \cos(\omega \cdot t - \phi) + i \cdot \varepsilon_0 \cdot \sin(\omega \cdot t - \phi)} \\
E^*(\omega) &= \frac{\sigma_0}{\varepsilon_0} \cdot cos\phi + \frac{\sigma_0}{\varepsilon_0} \cdot i \cdot sin\phi = E_1 + i \cdot E_2
\end{aligned}
\tag{1}
$$

where: σ_0 = stress amplitude [MPa], ε_0 = strain amplitude [‰], ω = angular frequency, ϕ = phase angle [°], E_1 = storage modulus [MPa], E_2 = loss modulus [MPa].

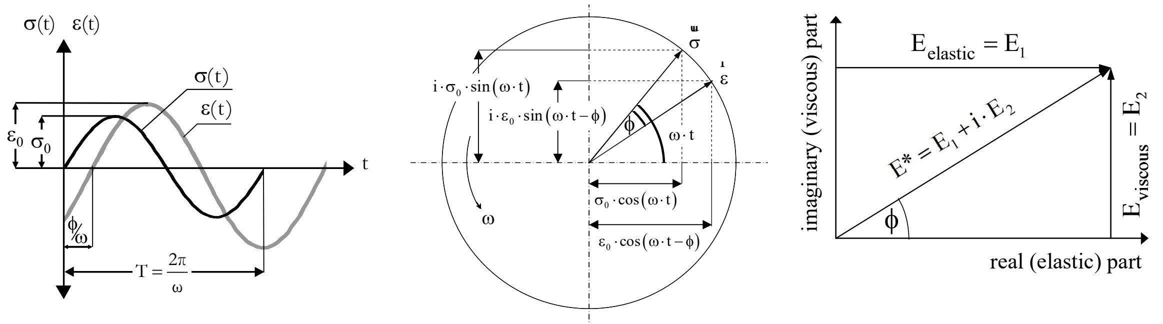


Figure 7. Oscillating stress *σ(t)* applied in a cyclic test on a linear visco-elastic material, and resulting strain *ε(t)* lagging behind by the phase angle *ϕ* (left); representation of *σ(t)* and *ε(t)* in terms of complex numbers (middle); derivation of the storage modulus E_1 and the loss modulus E_2 from the real part and the imaginary part of the stiffness modulus (right) (Wistuba et al., 2009).

The term E_1 in Equation 1 is in phase with the strain and is the real part of the complex modulus (cp. Figure 7, right), called storage modulus, while the second term E_2 represents the imaginary part of the complex modulus, called loss modulus. For the material characterisation and specification, the norm (absolute value) of the complex modulus $|E|$ is usually calculated (cp. Equation 2). Due to the asphalt mixture visco-elastic properties, complex modulus is highly temperature and loading frequency dependent.

$$|E^*| = |E| = \sqrt{\left(\frac{\sigma_0}{\varepsilon_0} \cdot cos\phi\right)^2 + \left(\frac{\sigma_0}{\varepsilon_0} \cdot i \cdot sin\phi\right)^2} = \sqrt{E_1^2 + E_2^2} = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

b) Dissipated energy

Beside complex modulus, the dissipated energy is commonly used for the characterization of material visco-elastic properties under cyclic loading. The energy dissipated within one loading cycle represents the difference between the energy provided to the material during the loading phase and the energy released during unloading. If a material is perfectly elastic, the loading and unloading curves follow the same paths, meaning that all the energy is recovered, without any energy dissipation (see Figure 8, left). In case of viscoelastic materials such as asphalt mixture, loading and unloading curves do not overlap, which indicates loss of energy within the material (see Figure 8, right). Part of the energy is dissipated from the system through external work, heating or damage (Ghuzlan and Carpenter, 2000).

The ellipse generated by the loading and unloading phases is called hysteresis loop and its area corresponds to the energy dissipated in one loading-unloading cycle (Figure 8, right). For the calculation of dissipated energy (W_n) in one loading cycle, the following equation can be used:

$$W_n = \pi \cdot \sigma_n \cdot \varepsilon_n \cdot sin\phi_n \quad [\mathrm{kJ/m^3}], \tag{3}$$

where: σ_n = stress amplitude at cycle n [MPa], ε_n = strain amplitude at cycle n [‰], ϕ_n = phase angle at cycle n [°].

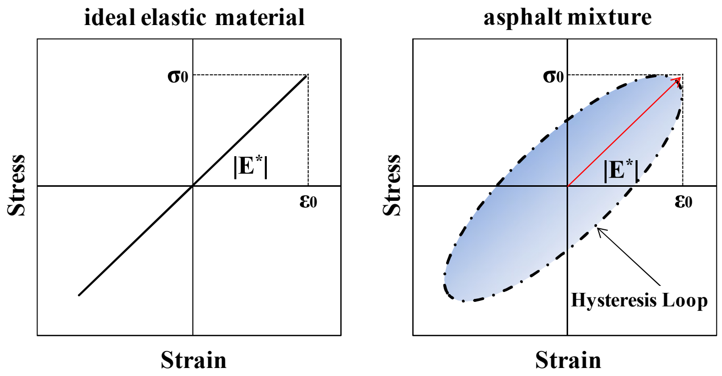


Figure 8. Loading cycle in a strain-stress diagram for a perfectly elastic material (left), and for a visco-elastic material such as asphalt mixture (right).

The dissipated energy is a good instrument for observing material behavior during cyclic loading (Carpenter and Shen, 2006), because it considers both stress/strain and phase angle parameters. As reported by Di Benedetto (2013), the change in asphalt mixture mechanical properties in a fatigue test can be characterized by the change of the hysteresis loop form during cyclic loading, which directly corresponds to the change in dissipated energy.

c) Test types for evaluation of asphalt mixture fatigue resistance

For determination of asphalt mixture fatigue resistance several test types are used, differing in loading mode and specimen shape (see Figure 9): homogeneous or non-homogeneous (uniaxial, indirect, bending tests), in tension mode or in tension-compression mode, in stress or in strain controlled mode (cp. EN 12697-24).

For all test types, a standard machine equipped with climate chamber, loading cell able to apply sinusoidal loading, and LVDTs for strain measurements at asphalt specimen are used.

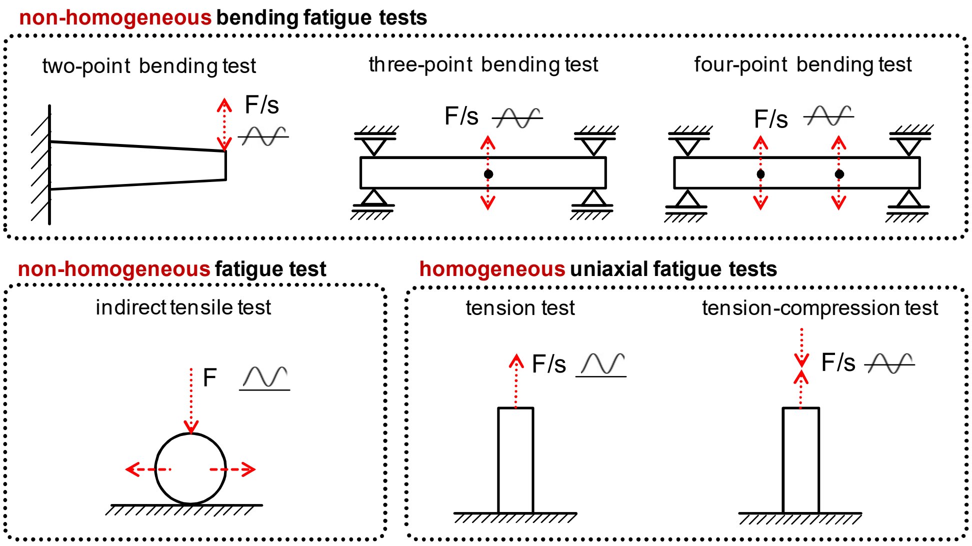


Figure 9. Cyclic test usually employed for evaluation of asphalt mixture fatigue resistance (F = force, s = deformation).

A non-homogeneous fatigue test implies a non-uniform stress/strain state in asphalt sample across its cross-section during fatigue excitation. Due to these stress/strain inhomogeneities, non-homogeneous fatigue tests have shown several disadvantages when a rigorous analysis of fatigue process is desired (Soltani and Anderson, 2005). With the occurrence of damage, the stress and strain distributions become nonlinear and the complex modulus changes disproportionally within the specimen in an unknown manner. In contrary, the stress state in the material in uniaxial fatigue tests is relatively uniform across the specimen cross-section (Johnson, 2010), and a direct access to the rheological properties of material is possible (Di Benedetto et al., 1996). However, it is quite difficult to keep this homogenous state, which could be disturbed due to some imperfections e.g. geometry of the apparatus, edge effects, sample heterogeneity (Di Benedetto et al., 1996).

Furthermore, almost all fatigue tests (with the exception of indirect tensile test) presented in Figure 9 can be performed either in strain or in stress controlled mode. In strain controlled mode, the constant strain amplitude, measured at asphalt specimen, is maintained over the whole test duration. Consequently, the material response given in terms of stress amplitude decreases as a result of the specimen damage, regardless of whether a tension or a tension-compression strain signal is applied (cp. Figure 10, a, b). In opposite to strain controlled mode, in stress controlled mode, the constant stress amplitude applied to the specimen is maintained over the whole test duration. Consequently, the elastic strain amplitude tends to increase until specimen failure (in case of loading is controlled in terms of a tensile-compressive stress amplitude) (cp. Figure 10, c). If only tensile stress amplitude is applied to asphalt sample (cp. Figure 10, d), the fatigue phenomenon could be hidden by the accumulation of irreversible (plastic) strain (cp. Di Benedetto et al., 2004). This is particularly related to indirect tensile test and uniaxial tension test (cp. Figure 9).

Besides conventional continuous cycling loading, where constant strain/stress amplitude is maintained over the whole test duration, recent research studies showed that an accelerated fatigue tests in form of amplitude sweep can be successfully used for fully fatigue evaluation of both bitumen and asphalt mixture. Amplitude sweep test consists of stepwise increase of strain/stress amplitude until specimen failure. This type of test appears to have the ability to indicate fatigue resistance as obtained by the conventional fatigue test with a constant strain/stress evolution (Johnson, 2010; Pérez Jiménez et al., 2013; Hintz and Bahia, 2013).

Concerning the appropriate mode of loading in fatigue tests (stress or strain controlled mode), some researchers gave recommendations depending on the total thickness of pavement asphalt layers:

- The constant stress mode of loading is generally considered applicable to asphalt mixtures for thick asphalt pavements (total asphalt thickness > 15 cm, acc. to Jacobs, 1995; total asphalt thickness > 20 cm, acc. to NCHRP, 2004), because in this case, the asphalt layers are a main load-carrying component. Although stiffness reduction occurs due to fatigue effects under repeated loading, due to the high total asphalt thickness, the changes in the stress are not significant and lead to a relatively constant stress situation (cp. NCHRP, 2004).

- The constant strain mode of loading is generally considered applicable to asphalt mixtures for thin asphalt pavements (total asphalt thickness < 5 cm, acc. to NCHRP, 2004; total asphalt thickness < 8 cm, acc. to Jacobs, 1995), because in this case, the asphalt layers are not the main load-carrying component. In this case, the strain in the asphalt layers is governed by the underlying layers and is not greatly affected by the change in the asphalt layer stiffness due to the fatigue effects under repeated loading. Therefore, a constant strain situation in asphalt layers is expected (cp. NCHRP, 2004).

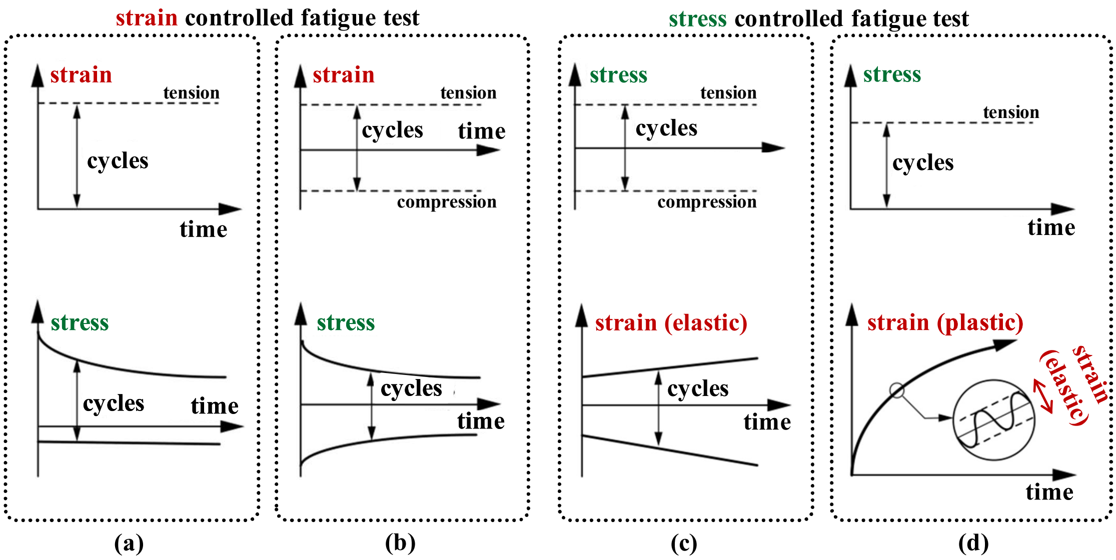


Figure 10. Schematic representation of loading modes in fatigue tests: strain controlled (a), (b) (with corresponding stress response) and stress controlled (c), (d) (with corresponding strain response) (acc. to Di Benedetto, 1996).

Since several test types are used, there is no consensus between researchers about the adequate test method for determining the asphalt mixture fatigue resistance. Research supporting this question is presented in Publication A (see Section 4) of this thesis.

d) Asphalt mixture response under continuous cyclic loading

If continuous cyclic loading is applied on a pre-fabricated asphalt specimen using one of the above-mentioned test types, material damage is associated with the loss in norm of complex modulus as the number of loading cycles increases, regardless of the mode of loading (Ghuzlan and Carpenter 2000; Underwood, et al., 2012). In general, three phases of the complex modulus decrease are distinguished (cp. Baaj et al., 2003) (see Figure 11):

- Phase I is represented by a rapid decrease of the complex modulus which cannot be explained by fatigue damage only. The complex modulus decrease in this phase is highly influenced by biasing effects such as self-heating, thixotropy, and nonlinearity (cp. Babadopulos, 2017) (see Section 2.2).

- Phase II is represented by the quasi-stationary decrease of the complex modulus, where the role of fatigue on complex modulus decrease is predominant. Phase I and Phase II correspond to the initiation and propagation of a network of micro-cracks.
- Phase III: During this phase a macro-crack appears by coalescence of the micro-cracks and propagates inside the material, leading to failure of the asphalt specimen.

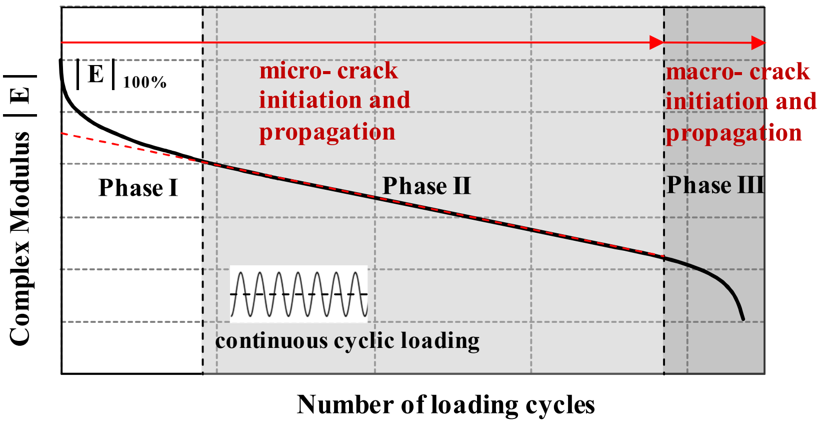


Figure 11. Three phases of complex modulus evolution in one fatigue test (schematic).

During continuous cycling loading of an asphalt specimen, the dissipated energy evolutes in three-phases depending on loading mode (see Figure 12). In fatigue test in stress controlled mode, dissipated energy increases with each loading cycle. This is a consequence of the increased material deterioration, where strain amplitude continually increases (see Figure 12, left). On the contrary, in fatigue test in strain controlled mode dissipated energy decreases with each loading cycle (see Figure 12, right). This is due to the steady material damage, where, with each loading cycle, less stress is needed in order to maintain the fixed strain amplitude.

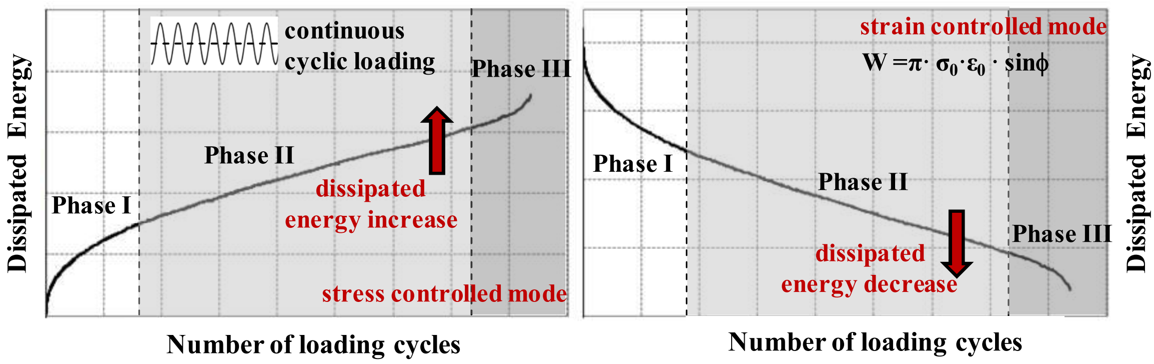


Figure 12. Dissipated energy evolution in fatigue test in stress controlled mode (left), and in fatigue test in strain controlled mode (right) (schematic).

The fatigue failure of the asphalt sample is usually considered as transition between Phase II and Phase III of complex modulus evolution. A precise determination of the cycle where macro-crack appears and propagates is a difficult task. Different failure criteria are proposed, which are related to the evolution of different test parameters such as complex modulus (EN 12697-24, 2012; Kim et al., 2003), dissipated energy (Hopman et al., 1989), complex modulus and number of loading cycles (Rowe and Bouldin, 2000). Among these failure criteria, the conventional approach acc. to the European Standard (EN 12697-24, 2012) and the energy ratio approach based on dissipated energy (Hopman et al., 1989) are widely used.

According to the European Standard (EN 12697-24, 2012), the fatigue failure is related to the number of loading cycles ($N_{f,50}$), where 50 % decrease in complex modulus occurs (see Figure 13).

The energy ratio ER approach relies on dissipated energy and represents the ratio between the initial dissipated energy, and the dissipated energy at cycle n, reading

$$ER_n = \frac{n \cdot W_0}{W_n} \quad [\text{-}], \tag{4}$$

where: W_0 = initial dissipated energy [kJ/m^3], W_n = dissipated energy at cycle n [kJ/m^3].

Typical examples of energy ratio evolution during fatigue tests in stress and strain controlled modes are shown in Figure 13. By plotting the energy ratio versus the number of loading cycles, the resulting fatigue failure for a test in stress controlled mode is related to the number of loading cycles when energy ratio reaches its maximum (cp. Figure 13, left).

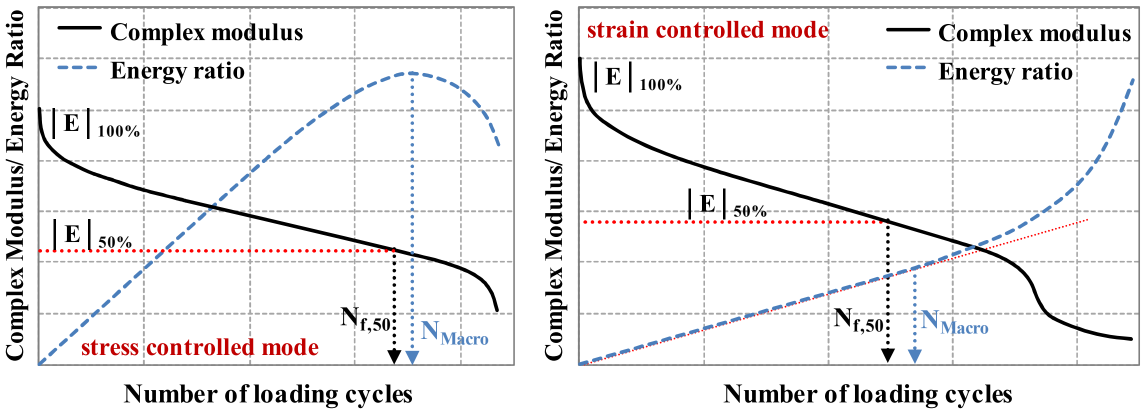


Figure 13. Determination of the number of loading cycles at failure using conventional approach acc. to European Standard (EN 12697-24, 2012), and using energy ratio approach based on dissipated energy (acc. to Hopman et al., 1989): fatigue test in stress controlled mode (left), fatigue test in strain controlled mode (right) (schematic).

The corresponding number of cycles (N_{Macro}) provides the point of transition from micro to macro cracking. In fatigue test in strain controlled mode, the resulting fatigue failure is related to the number of loading cycles when energy ratio leaves its asymptotic value (cp. Figure 13, right).

Using the conventional approach according to the European Standard (EN 12697-24, 2012), fatigue testing of one asphalt mixture relies on multiple test replicates at a single frequency, at a single temperature (in range from 10 °C to 30 °C), and at three different load amplitudes (stress or strain). For example, up to 18 single fatigue tests are performed according to the European Standard. From all tests, a unique fatigue curve in form of a potential function is drawn, which represents the number of loading cycles at failure (N_f) in function of the applied strain amplitude (or stress amplitude respectively in a stress controlled fatigue test) (see Figure 14):

$$N_f = k_1 \cdot \varepsilon^{k_2} \quad \text{[-], for strain controlled mode}$$
$$N_f = k_1 \cdot \sigma^{k_2} \quad \text{[-], for stress controlled mode} \qquad (5)$$

where: N_f = number of loading cycles at failure (fatigue life) [-], k_1, k_2= regression parameters [-], ε = strain amplitude [‰], σ = stress amplitude [MPa].

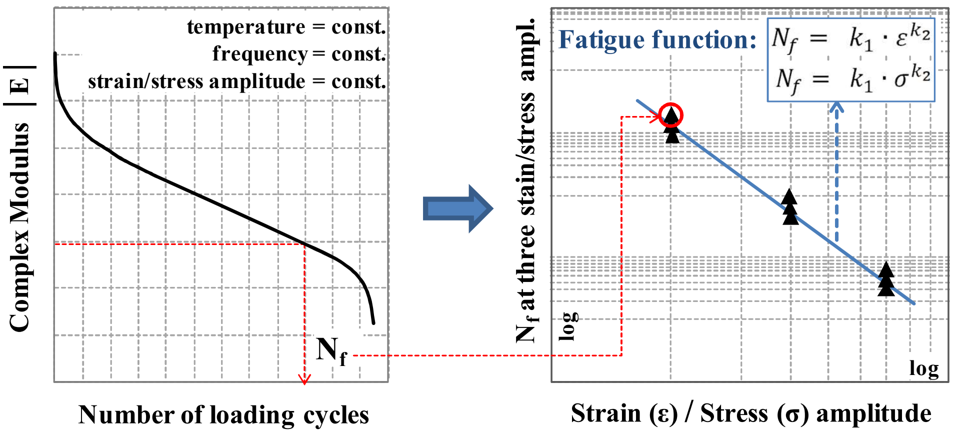


Figure 14. Fatigue function of specific asphalt mixture obtained performing multiple fatigue tests at a single frequency, at a single temperature, and at three different load amplitudes (stress or strain).

This specific fatigue function determined at a single temperature is used as a key performance property for the durability of asphalt mixtures in general. As asphalt fatigue behaviour is driven by the temperature-dependent rheological properties of the bitumen to a non negligible extent, numerous authors claim that asphalt fatigue properties are highly dependent on test temperature (see e.g. Ghuzlan and Carpenter, 2003; NCHRP, 2004; Mollenhauer and Wistuba, 2009; Bodin et al., 2010). Therefore, fatigue function determined at a single temperature, although in best accordance with European Standard, cannot be representative for the whole in-service-temperature range. If considered in such a way, this may provoke misleading conclusions, particularly if the fatigue results are used for pavement design purposes. This is especially important for advanced asphalt mixtures with diverse additives and high reclaimed asphalt content, where little or no experience exists in their long-term behaviour in-situ.

Therefore, plausible evaluation of asphalt mixture fatigue resistance requires consideration of a wide temperature range. The main issue in this objective is to minimize the laboratory effort if compared to the procedure in accordance with the European Standard (EN 12697-24, 2012). Research supporting such a testing procedure is represented in the Publication B (see Section 4) of this thesis.

2.2 Testing recovery properties of asphalt mixtures

Actual service life of the asphalt pavement is significantly longer than measured in laboratory by means of continuous fatigue tests at fixed frequency and temperature (Van den Bergh, 2011). This is due to the effects of environmental conditions, traffic and differences in geometry, and real conditions in pavement when compared to laboratory test setups (Molenaar, 2007). Also self-healing is a significant factor (cp. Van den Bergh, 2011), since traffic loading in-situ is not continuous, occurs rather random with different rest period durations (cp. Figure 3).

Therefore, the laboratory evaluation of self-healing properties of asphalt mixtures is fundamental for improving the mix design and the in-field response of asphalt pavements. Since self-healing represents the opposite mechanism of fatigue, it is usually addressed by the same test types (cp. Figure 9), but by introducing rest period(s) of various durations (discontinuous test). During rest period(s), asphalt specimen is in a stress-free condition. Two different approaches for introducing rest period(s) can be used (Shen and Carpenter, 2007):

- a single rest period after a pre-defined number of loading cycles (Figure 15, left), or
- a rest period after each loading cycle (Figure 15, right).

Figure 15. Two approaches for introducing rest period(s) (RP) to interrupt cyclic loading for the evaluation of self-healing properties: a single rest period after a pre-defined number of loading cycles (left), a single rest period after each loading cycle (right).

The first method simulates loading conditions in the field in a less realistic manner, as in-situ rest periods of different durations occur randomly. However, in laboratory, this method provides better insight into the change of the material properties in consequence of a single rest period of longer duration, as demonstrated in recent studies (Wistuba et al., 2013; Isailović et al., 2016 a). If applying a very short rest period after each loading cycle, the effect of recovery of material mechanical properties during one rest period cannot be identified easily.

As observed in continuous fatigue tests, a significant loss in norm of complex modulus is observed as the loading cycles increase (cp. Figure 11). If loading is interrupted during the test by introducing a rest period between two continuous loading phases (cp. approach in Figure 15, left), a substantial recovery of the complex modulus may be observed (see Figure 16, red line). This complex modulus recovery is usually ascribed to the self-healing properties of the asphalt mixture (Breysse et al., 2005; Tan et al., 2012). After the rest period of a sufficient duration, asphalt sample can behave as undamaged and may sustain a similar number of loading cycles until the same complex modulus drop.

Furthermore, if a relatively short rest period is introduced after each loading cycle (cp. approach in Figure 15, right), the complex modulus does not exhibit such fall/increase as a consequence of the shortness of both loading phase and rest period, respectively (see Figure 16, green line). In this case, the complex modulus recovery during each rest period lead to a relatively smooth complex modulus evolution.

Due to the effects of material recovery during rest period(s), the asphalt mixture fatigue resistance in terms of number of loading cycles at failure is significantly extended in both cases, when comparing to results from continuous fatigue tests without rest period(s) application (see Figure 16, black line).

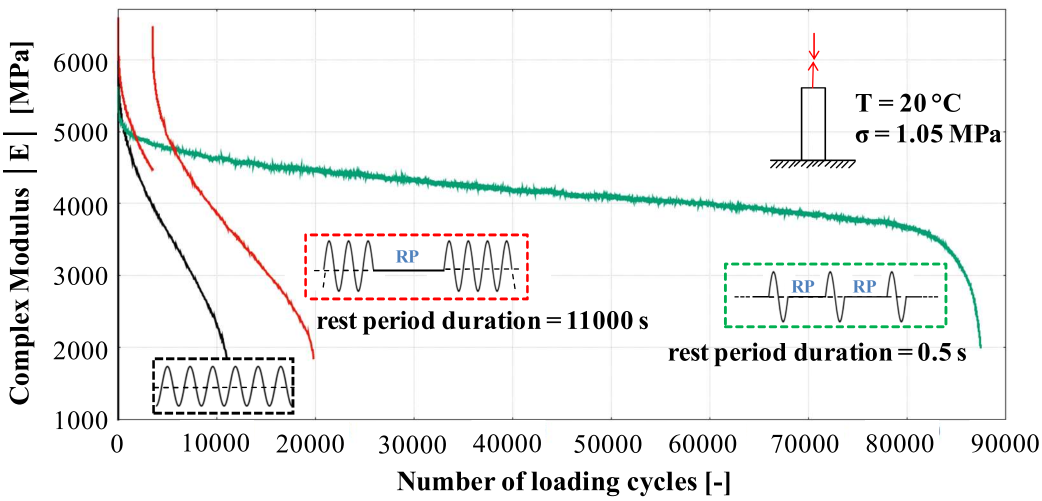


Figure 16. Evolution of complex modulus in continuous fatigue test (black line), in discontinuous fatigue test with a single rest period (11000 seconds) after a pre-defined number of loading cycles (red line), and in discontinuous fatigue test with a rest period (0.5 second) after each loading cycle (green line). Results are based on uniaxial tension-compression test in stress controlled mode, at test temperature of 20 °C, and at stress amplitude of 1.05 MPa.

As mentioned above, the self-healing property is usually related to the recovery of the complex modulus during rest period that leads to the prolonged fatigue life of asphalt mixture. However, recent research studies show that any change in the complex modulus either during cyclic loading or during rest period is not solely related to pure effects of fatigue and self-healing only (Di Benedetto et al., 2011; Mangiafico et al., 2015). The complex modulus decrease during cyclic loading, and accordingly, increase during rest period is significantly affected by the additional biasing phenomena such as nonlinearity, self-heating and thixotropy (cp. Babadopulos, 2017) (see Figure 17):

- Nonlinearity is a consequence of the nonlinear visco-elasticity of asphalt mixtures, where the ratio between stress and strain in terms of complex modulus is not constant and depends on the loading level. For asphalt mixtures, the linear visco-elasticity is considered for a very low strain/stress levels (cp. Airey et al., 2002). The effect of nonlinearity in cycling loading disappears when specified strain/stress amplitude is achieved.
- Self-heating is characterized through viscosity change represented by the temperature increase in asphalt specimen during cyclic loading. This effect is caused by the mechanical dissipation of energy in the bituminous mixture (Di Benedetto et al., 2011).
- Thixotropy is characterized through viscosity change as a consequence of the material microstructure rearranging (called microstructure breakdown) during cyclic excitation (Barnes, 1997).

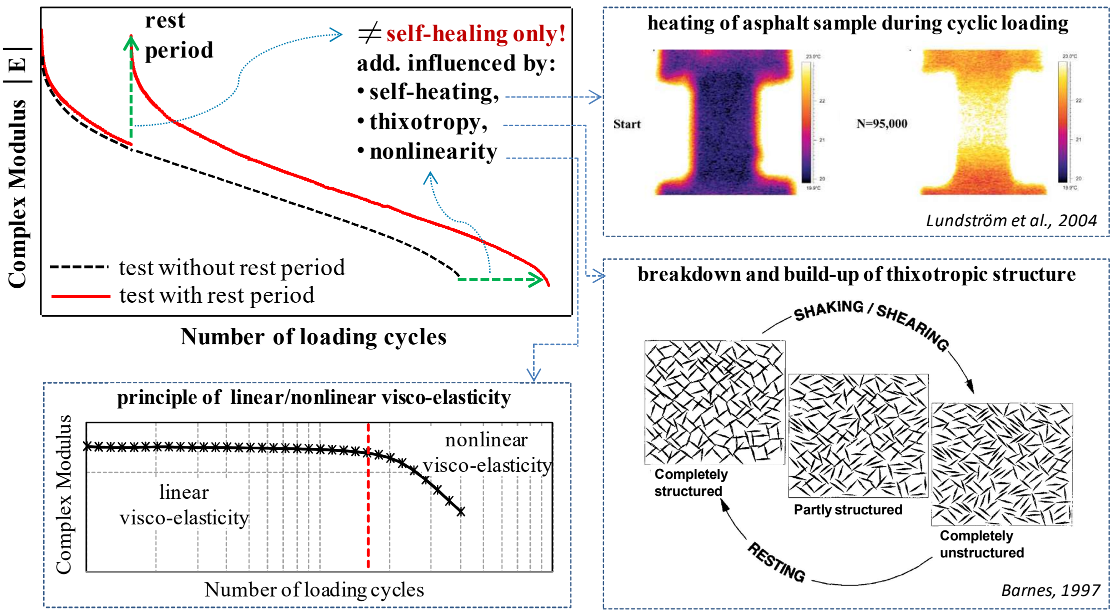


Figure 17. Evolution of complex modulus in continuous and in discontinuous fatigue test with a single rest period (schematic) (left, top); detail on self-heating of asphalt sample during cyclic loading (Lundström et al., 2004) (right, top); schematic representation of breakdown and build-up of thixotropic structure (Barnes, 1997) (right, bottom); principle of linear/nonlinear visco-elasticity (left, bottom).

Since all these effects are completely reversible during rest period of sufficient duration (the temperature inside of specimen decreases and achieves the initial point, material microstructure builds up), they cannot be accounted for self-healing and have to be separately considered. Therefore, using the term "recovery" in place of "self-healing" appears to be more accurate and comprehensive if conducting laboratory investigation in this way. It is worth to mention that biasing effects are barely experienced in-situ that is due to the specific loading conditions (cp. Lundström et al., 2004; Babadopulos, 2017).

Recovery capability of bitumen and asphalt mixtures has been investigated in laboratory by many researchers, both at the micro and macro scale (Daniel, 1996; Phillips, 1998; Little et al., 1999; Breysse et al., 2003; Bodin et al., 2004; Carpenter and Shen, 2006; Kim and Roque, 2006; Bhasin et al., 2009; Santagata et al., 2009; Di Benedetto et al., 2011; Kringos et al., 2011; Nazzal et al., 2012; Palvadi et al., 2012; Tan et al., 2012; Shan et al., 2013; Santagata et al., 2013; Moreno-Navarro et al., 2015; Ayar et al., 2016). In these studies a high dependency of binder and mixture recovery potential was observed and linked to specific material properties (bitumen composition and bitumen morphology, bitumen content, aggregate particle gradation, binder viscosity, air voids content, etc.) and external conditions (test configuration, test temperature, loading, and rest period type and duration). Due to the application of different materials and test methods, some influencing parameters are not well assessed because of contradicting or non-plausible test results, e.g. effects of bitumen polymer modification (positive effect on recovery properties, acc. to Shen and Carpenter, 2007; no effect on recovery properties, acc. to Kim and Roque, 2006; negative effect on recovery properties, acc. to Qiu, 2012), ageing conditions (negative effect on recovery properties, acc. to Little et al., 1999; positive effect on recovery properties, acc. to Van den Bergh, 2011). More research on this subject is presented in Publication C (see Section 4) of this thesis.

As a consequence of the variety of introduced test methods and investigated asphalt mixtures, so far no test protocol for quantifying the recovery capability in asphalt pavements has been internationally established and is widely accepted (Ayar et al., 2016). Some approaches are focusing on results from discontinuous tests only, where recovery of mechanical/rheological material parameters (e.g. complex modulus, phase angle, dissipated energy) is observed and evaluated during rest period(s). Even though this procedure represents a practical tool for evaluating the recovery properties during the rest period, the influence of rest period on the overall fatigue life extension cannot be assessed.

Therefore, the main approach for assessing the recovery properties of asphalt mixtures relies on comparing the responses (e.g. number of loading cycles until failure) under loading conditions with and without rest period(s) (Qiu, 2012). This comparison is usually quantified by a recovery index (cp. Little et al., 2001; Santagata et al., 2009, see Equation in Figure 18). The higher the recovery index, the higher is the recovery potential of a particular asphalt mixture. However, due to the large scattering of the experimental results it could arise that fatigue life of the discontinuous test with rest period(s) is even shorter than fatigue life of the continuous fatigue test without rest period(s), showing a negative recovery index (see Figure 18). This may lead to an erroneous evaluation of the recovery potential. Until now, little effort has been put on the derivation of an effective recovery index applicable for evaluation of the recovery potential of specific asphalt mixture that overcomes the effects originating from the tremendous scatter of the experimental results. Research supporting this subject is represented in Publication D (see Section 4) of this thesis.

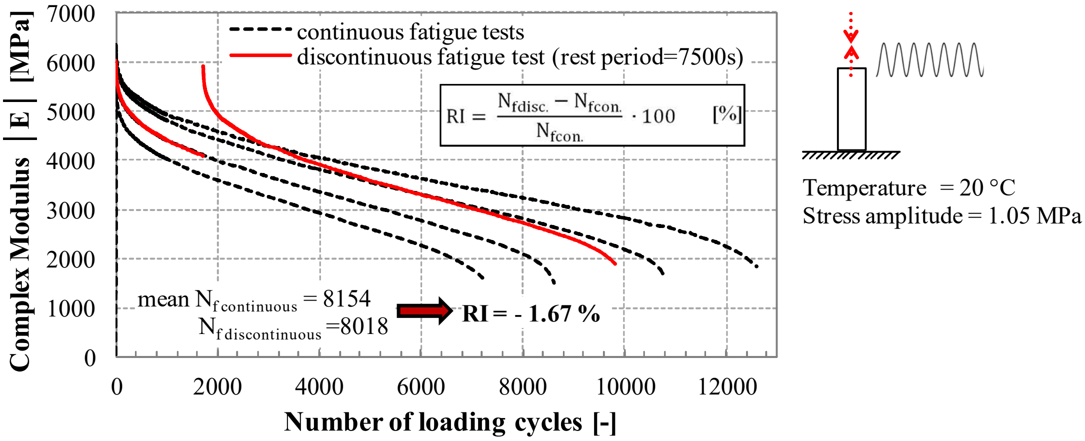


Figure 18. Example of the evolution of complex modulus in function of number of loading cycles in continuous and discontinuous (with single rest period) uniaxial tension-compression fatigue tests in stress controlled mode (Wistuba et al., 2013).

Since most of the conducted research deals with the overall (bulk) recovery properties, only limited work addresses the real self-healing potential of asphalt mixtures. This is only possible by correctly identifying, qualifying, and separation of the above-mentioned biasing effects from the experimental results. These cyclic effects were investigated by some researchers (Lundström et al., 2004; Soltani and Anderson, 2005; Di Benedetto et al., 2011; Mangiafico et al., 2015; Babadopulos, 2017), but until now no research work was successful in quantifying the real self-healing effect, because separation of self-healing from thixotropy seems to be a quite difficult task. The effects associated with thixotropy seem to be most responsible for the recovery of asphalt mixture performance properties during rest period.

A reliable quantification of biasing effects is only possible if some specific laboratory conditions are fulfilled (e.g. accurate stress/strain measurements, adequate measurement of temperature variation in asphalt sample). For quantification of the self-heating effect, temperature measurements are usually carried out by inserting a small temperature sensor into the asphalt sample after compaction (cp. Di Benedetto et al., 2011; Mangiafico et al., 2015). This procedure requires drilling a hole in the asphalt sample that may result in weakening the material locally and in a substantial deviation of the stress field. Consequently, the experiential results could be affected significantly.

Furthermore, limited scientific work was dedicated to observing biasing effects in stress controlled mode, where the influence of self-heating effect may be different (due to the different temperature evolution) if compared to tests in strain controlled mode. However, the influence of rest period duration on recovery properties of asphalt mixtures considering biasing effects still remains unclear. Research supporting these subjects is represented in Publication E (see Section 4) of this thesis.

2.3 Testing of fatigue at asphalt mixture layers' interface

Since the interaction between asphalt layers in-situ is not that strong to prevent any relative displacement between them during traffic loading (Tozzo et al., 2014), fatigue may result in a degradation of asphalt mixture layers' interface.

Interface bonding properties in asphalt pavements are mostly evaluated using destructive static (monotonic) laboratory test methods, because of their simplicity and short test procedure. Due to the absence of standard technical regulations of the testing mode, the number of different monotonic test variants have been developed over the years: torque tests, wedge splitting test (Tschegg et al., 1995), direct shear test (Leutner, 1979), ASTRA test (Santagata and Canestrari, 1994), shear test from Romanoschi and Metcalf (2002), modified direct shear test (Raab and Partl, 2004), FDOT test (Sholar et al., 2004), NCAT shear test device (West et al., 2005), etc. The differences between these tests are reflected in loading conditions, specimen geometry and preparation, as well as test temperature. Based on test configurations or loading procedures, the destructive interlayer test methods are grouped into four categories (acc. to Canestrari et al., 2013): torque test, tensile test (pull-off test), wedge splitting test, and shear test (see Figure 19).

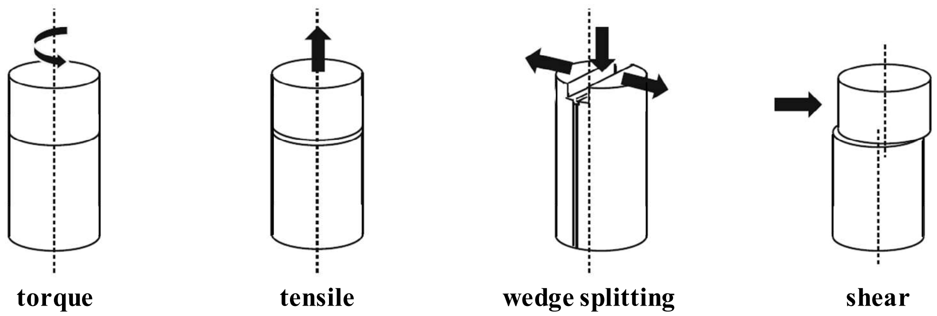
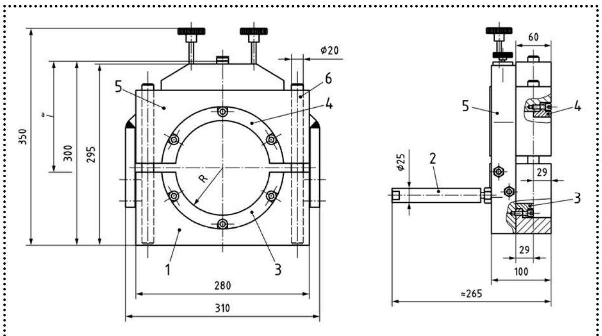


Figure 19. Working schemes of destructive interlayer tests (Canestrari et al., 2013).

Among these test configurations, the most popular test configuration for laboratory assessment of bonding condition is based on direct shear testing. In this procedure, a constant shear displacement rate is applied across the layers' interface of a double-layered asphalt sample until interface failure occurs. The typical result of this type of test is characterized by shear strength, obtained as the peak of the shear force. Figure 20, right shows the evolution of shear force over displacement in commonly used monotonic direct shear test designed by Leutner (1979) (see Figure 20, left).

Additionally to the direct shear load at layers' interface, some monotonic test configurations include application of a stress perpendicular to the interface (normal stress) in order to simulate the vertical traffic load more realistically (see ASTRA test, shear test from Romanoschi and Metcalf (2002), NCAT shear test device). Beside this enhancement, the obtained shear strength from monotonic shear tests is generally not seen as an appropriate indicator for the long-term (fatigue) interface performance evaluation, because the generated shear strain is not cyclic. Usually, shear strength is used as a key parameter for quality control to check if sufficient bonding was achieved during paving and compaction of the asphalt layers.



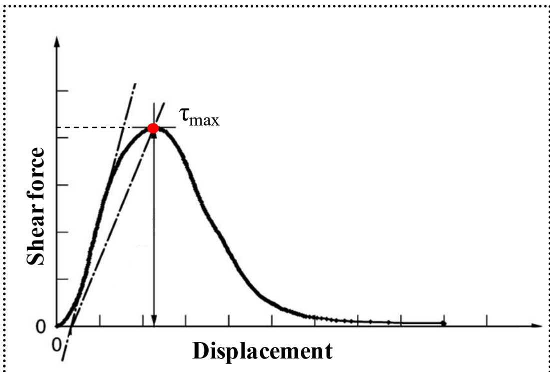


Figure 20. Monotonic direct shear test setup designed by Leutner (1979) (left), and corresponding evolution of shear force over displacement until interface failure (right).

In order to simulate field conditions more realistically, cyclic test methods have been developed more recently (Crispino et al., 1997; Carr, 2001; Romanoschi and Metcalf, 2001; Wellner and Ascher, 2007; Diakhate et al., 2011; Gorszczyk and Malicki, 2012; Tozzo et al., 2014; Zofka et al., 2015) (see Figure 21).

Most of these tests are based on direct shear testing, where asphalt mixture specimen (cylindrical or prismatic) is exposed to both cyclic shear load parallel to the interface, and static normal load perpendicular to the interface. The exceptions are double shear test from Diakhate et al. (2011) and shear test from Gorszczyk and Malicki (2012), where the additional static normal load cannot be applied. On the contrary, Romanoschi and Metcalf (2001) designed indirect shear tests, where both shear load and normal load are cyclically applied. This is due to the specific loading conditions, where longitudinal axis of the specimen forms an angle of 25.5° with the vertical, so that the shear load at the interface is half the normal load (see Figure 21). The SISTM device developed by Tozzo et al. (2014) brings some enactments if comparing to the solution from Romanoschi and Metcalf (2001), where additional loading of the double-layered asphalt sample by the weight of test device is avoided. Additionally, the angle between longitudinal axis of the specimen and vertical axis is set to 60°.

Among all these cyclic tests, only test apparatus developed by Wellner and Ascher (2007) has not been used for evaluation of fatigue properties of asphalt mixture layers’ interface. This type of test was solely employed for the evaluation of the temperature and frequency dependent interface shear stiffness.

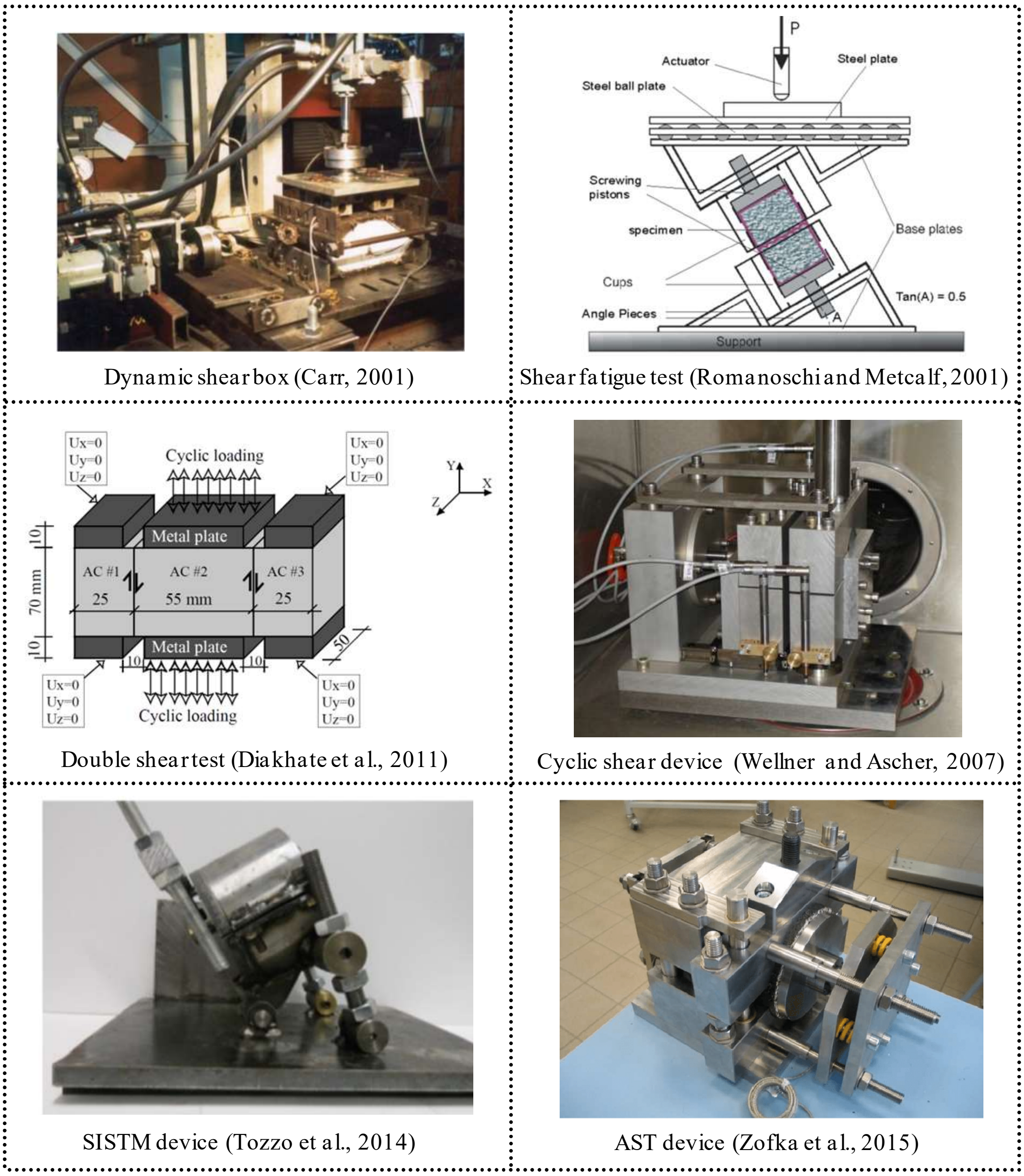


Figure 21. Some of cyclic shear tests used for evaluation of asphalt mixture layers' interfaces.

So far no internationally recognized method or procedure was established and accepted for standardization. Due to the variety of existing procedures, based primarily on different loading conditions (direct or indirect shear loading, temperature, loading frequency), test geometries and different methods for data analysis, direct comparison of test results from these shear tests is very complex. This is clearly shown in Figure 22 where different fatigue tests result in different parameters: interface shear stiffness modulus in direct shear test (Diakhate et al., 2011) and permanent shear displacement (PSD) at layers' interface in indirect shear test (Romanoschi and Metcalf, 2001). In this case, the direct comparison between test results is not possible. In extreme cases, the test results can be contradictory, and hence, standardization is needed.

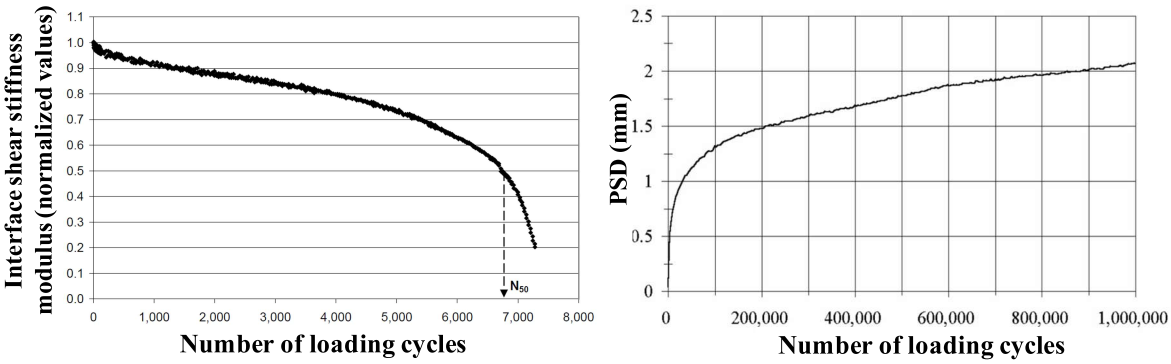


Figure 22. Resulting parameters from different fatigue shear tests: interface shear stiffness modulus evolution (normalized values) over number of loading cycles in direct shear test (Diakhate et al., 2011) (left), and evolution of permanent shear displacement (PSD) at layers' interface over number of loading cycles in indirect shear test (Romanoschi and Metcalf, 2001) (right).

As to the evaluation of asphalt mixture layers' interface fatigue properties, no comprehensive research effort has been dedicated to the assessment of both test dependent parameters (e.g. stress conditions and test temperature) and material dependent parameters (e.g. type of asphalt mixture, type and amount of tack coat application, preparation of asphalt samples). The existing research studies only focused either on specific test conditions or on specific material parameters. Furthermore, a barely comparison between monotonic and cyclic tests were conducted in order to investigate if the results from monotonic shear tests correlate with results from cyclic tests. Research supporting these subjects is represented in Publication F and Publication G (see Section 4) of this thesis.

3 Summary of the Publications A to G

3.1 Research objectives

As shown in previous sections, a lot of work has been done for laboratory characterization of asphalt fatigue and recovery properties that are crucial for asphalt mixture optimization and prediction of pavement's service life. However, there are still a number of research questions to be answered:

- What is the adequate test configuration that allows plausible characterization of asphalt mixture fatigue resistance, and if existing, is there any possibility to reduce time-consuming laboratory testing when considering the asphalt fatigue temperature dependency?
- How can laboratory evaluation of the recovery properties of asphalt mixtures be improved, where the extensive scattering of the experimental results becomes irrelevant? How do biasing effects, observed during cyclic loading, influence the recovery properties in stress controlled tests, and does their influence change with the change in rest period duration?
- Can cyclic shear test apparatus introduced by Wellner and Ascher (2007) be used for fatigue evaluation of the layers' interface and, if so, what is the influence of various test and material parameters on interface fatigue properties? Are the outcomes from monotonic shear tests comparable with outcomes from cyclic fatigue shear tests?

In order to clarify these research questions, the following objectives were defined to be answered in Publications A to G:

- Find an appropriate test configuration that allows plausible characterization of asphalt mixture fatigue resistance by comparing different test types specifically selected (Publication A).
- Develop a new fatigue protocol (using the appropriate test configuration from the previous objective) that considers the asphalt fatigue temperature dependency, without significantly increasing laboratory effort if compared to the procedure in accordance with the European Standard (EN 12697-24, 2012) (Publication B).
- Clarify the dubiety about the factors influencing asphalt mixture recovery properties, especially bitumen polymer modification and asphalt mixture ageing condition (Publication C).
- Develop a new procedure for laboratory evaluation of asphalt mixtures recovery properties, which can substantially and successfully mitigate the material-related scatter observed in the experimental results, allowing an accurate evaluation of the recovery potential (Publication D).

- Quantify the contribution of nonlinearity and self-heating effects to the recovery of asphalt mixture mechanical properties in discontinuous fatigue tests in stress controlled mode, and determine the change of their contributions with the variation of rest period duration (processed in Publication E).
- Investigate if the existing cyclic shear test apparatus introduced by Wellner and Ascher (2007) can be used for the fatigue evaluation of asphalt mixture layers' interface, and conduct a comprehensive investigation on the effect of different parameters such as normal stress conditions, test temperature, type of asphalt mixture, type and amount of tack coat emulsion, preparation of asphalt samples, on interface fatigue properties (Publication F).
- Investigate if the shear strength obtained from monotonic shear tests can be used as an indicator for the long-term interface shear performance, as observed under cyclic loading (Publication G).

3.2 Findings of research work presented in the papers

In this thesis, a detailed laboratory investigation was conducted on fatigue cracking effects both in asphalt mixture and at asphalt layers' interface, as well as on recovery properties of asphalt mixtures.

In respect to the research objectives the work is structured in the following publications (see Section 4):

A: Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests,

B: Sweep test protocol for fatigue evaluation of asphalt mixtures,

C: Investigation on mixture recovery properties in fatigue tests,

D: Experimental study on asphalt mixture recovery,

E: Influence of rest period on asphalt recovery considering nonlinearity and self-heating,

F: Fatigue investigation on asphalt mixture layers' interface,

G: Asphalt mixture layers' interface bonding properties under monotonic and cyclic loading.

Publication A aims in finding an appropriate test configuration that allows plausible characterization of asphalt mixture fatigue resistance. In this work, the comparison between different test types was limited to those in stress controlled mode, since this type of loading is generally considered applicable to asphalt mixtures for thick asphalt pavements (cp. Section 2.1). Therefore, following test types are considered: (i) non-homogenous indirect tensile test, (ii) homogenous uniaxial tension test, and (iii) homogenous uniaxial tension-compression test. Based on the almost same number of loading cycles at failure, comparison between these three test types becomes possible. The analysis of the mechanical properties evolution is performed using the dissipated energy approach, where the change of the hysteresis loop form and position was evaluated at the beginning of the test and at failure (N_{Macro}). Rotation and expansion of the hysteresis loops with increasing number of loading cycles are primarily due to material fatigue (or effects associated with fatigue), while horizontal shifting along the strain axis can be interpreted as a permanent deformation of the specimen.

The test results indicate that indirect tensile test and uniaxial tension test present comparatively little change in the material mechanical properties (small change of the loop form), with high accumulation of plastic deformation (big shift of the loop) (cp. results for indirect tensile test, Figure 23, left). On the other hand the uniaxial tension-compression test shows significant change in mechanical properties (approx. four times higher), with minimal plastic deformation (cp. Figure 23, right).

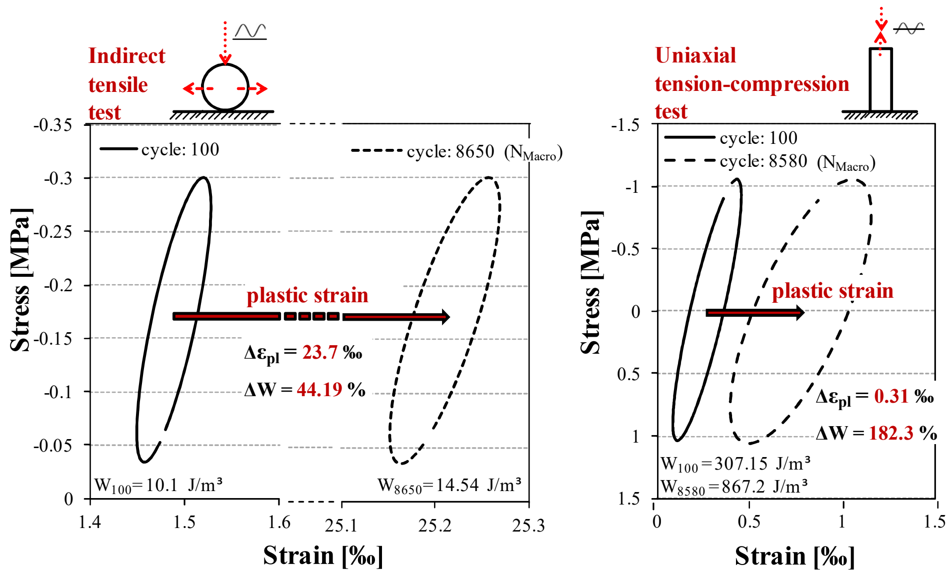


Figure 23. Hysteresis loops at cycle 100 and at failure (cycle N_{Macro}) for indirect tensile test (left) and uniaxial tension-compression test (right).

According to the test results, it can be concluded that indirect tensile test and uniaxial tension test at conventional test temperature of 20 °C are less appropriate tests for fatigue analysis, because the failure of asphalt specimen is primarily associated to the accumulation of permanent deformation, and barely in consequence of fatigue damage. Therefore, considering stress controlled mode of loading, the homogenous uniaxial tension-compression test seems to be the most appropriate for the fatigue evaluation of asphalt mixtures (see also Isailović and Wistuba, 2017). Therefore, this type of test represents a sound basis for fatigue (as well as recovery) evaluation of asphalt mixtures.

Publication B aims in developing a new fatigue protocol that considers the asphalt fatigue temperature dependency, since fatigue tests which are limited to a single temperature, although in best accordance with European Standard (EN 12697-24, 2012), cannot be representative for the whole in-service-temperature range. The main objective is to limit the increased laboratory effort to a minimum if comparing to the procedure in accordance with the European Standard.

The newly developed fatigue protocol is based on amplitude sweep test, performed using a uniaxial tension-compression test apparatus in stress controlled mode. The schematic procedure of the test protocol is represented in Figure 24. Prior to each amplitude sweep, a short frequency sweep is performed at the same asphalt specimen in order to determine the asphalt mixture visco-elastic properties. Instead of iso-thermal test conditions (as in accordance with the European Standard), the test temperature is varied in a range of -10 °C to 20 °C in order to cover the in-service-temperature range in a single procedure.

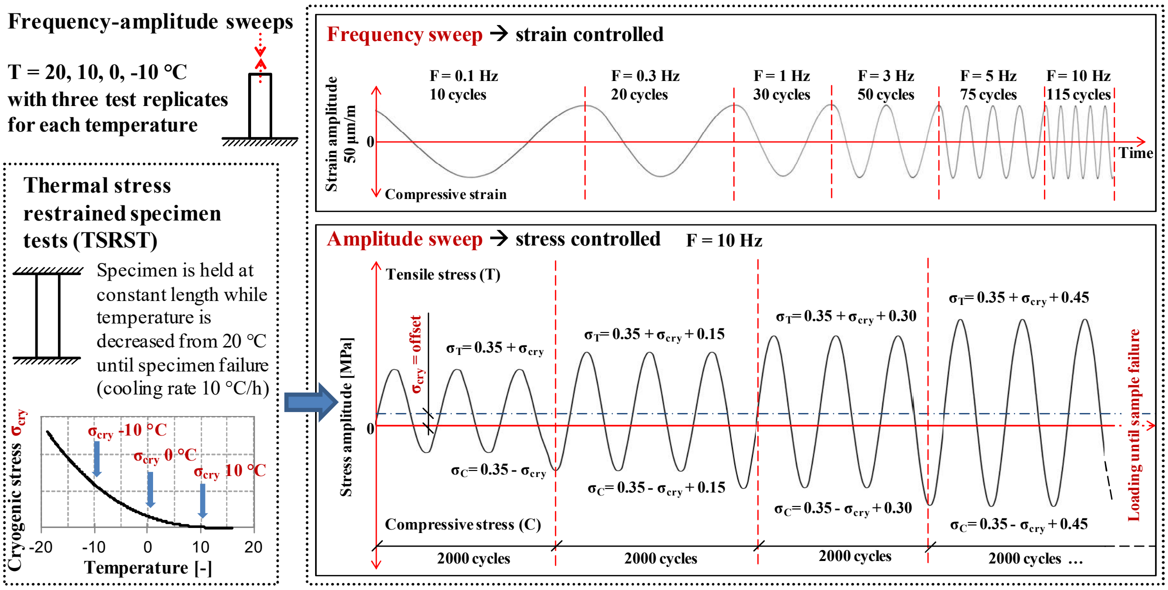


Figure 24. Schematic procedure of the new frequency-amplitude sweep test protocol; the cryogenic stress obtained from TSRST is considered for fatigue evaluation in amplitude sweep test at temperatures below 20 °C.

Considering fresh and aged asphalt mixtures, both sweep tests at four temperatures and conventional fatigue tests at two temperatures are performed. The research results indicate that the new test protocol can assess the fatigue resistance as observed in conventional fatigue tests (cp. Figure 25); the same ranking of asphalt mixtures by means of number of loading cycles at failure (N_{Macro}) is observed at 20 °C as well as at 0 °C.

The research results show that the conventional fatigue assessment restricted to a single temperature of 20 °C, although in best accordance with the European Standard, leads to misleading fatigue evaluation, since it results in better fatigue resistance for the aged asphalt mixture compared to the original fresh mixture (cp Figure 25, left). This is a direct consequence of fatigue temperature dependency negligence.

On the other hand, due to the temperature variation, a plausible evaluation of asphalt mixture fatigue performance obtained from amplitude sweeps is observed, where the fresh asphalt mixture shows significantly improved fatigue resistance compared to the aged one (cp. the area underneath the polynomial functions, Figure 25, right). Additionally, the simultaneous determination of complex modulus values at different temperatures and frequencies by frequency sweep allows for building a master curve, which provides a fundamental rheological understanding of visco-elastic materials such as asphalt mixture. Moreover, the new frequency-amplitude sweep test protocol relying on four temperatures requires a marginally increased laboratory effort if compared to conventional fatigue testing at single temperature (12 instead of 9 test samples), however, the plausible fatigue evaluation and determination of mixture viscoelastic properties are most beneficial.

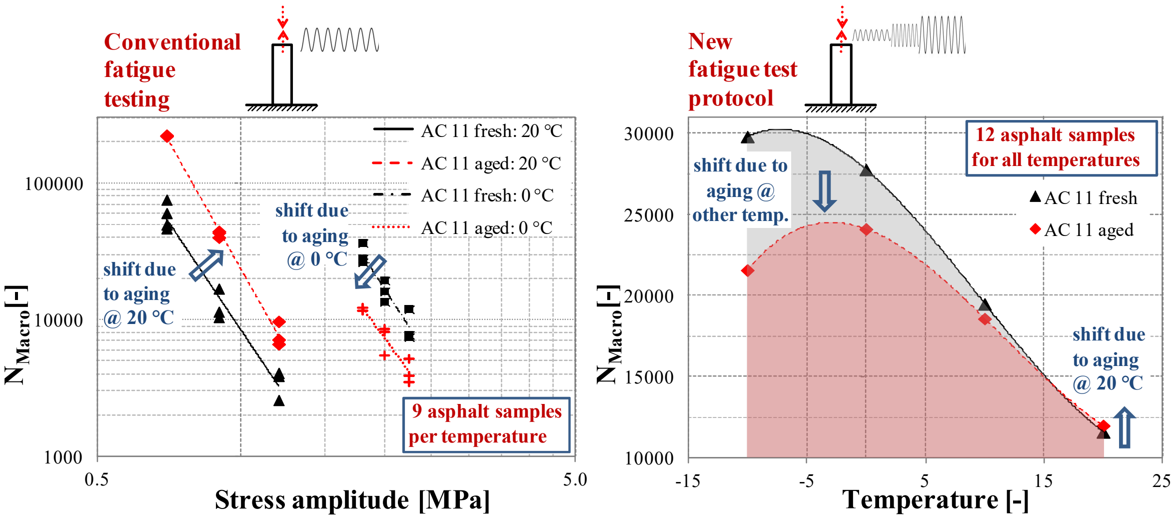


Figure 25. Fatigue functions of fresh and aged asphalt mixtures in conventional fatigue tests at 20 °C and 0 °C (left); resulting average number of loading cycles at failure N_{Macro} for fresh and aged mixtures (fitted with polynomial functions) in new fatigue protocol for 4 test temperatures from -10 °C to 20 °C (right).

Publication C aims in clarifying the dubiety about the factors influencing asphalt mixture recovery properties. Beside the bitumen polymer modification and asphalt mixture ageing condition, additional influencing factors are considered, such as asphalt mixture binder content, degree of compaction, and rest period duration. Recovery evaluation is based on discontinuous fatigue tests with single rest period (cp. Figure 26, left, top), using uniaxial tension-compression test in stress controlled mode. Based on the concept of dissipated energy, the recovery potential of asphalt mixture is determined through a relative change in dissipated energy observed at the beginning of the test and after the rest period (see Figure 26, left, bottom). The lower the absolute dissipated energy difference, the higher is the recovery potential of the asphalt mixture.

Most important research results are presented in Figure 26. Material recovery is extremely dependent on ageing. Aged samples show distinct lower ability to recover initial properties, which is in contrary to the theory from Van den Bergh (2011), and confirms the findings from Little et al. (1999). Ageing makes the binder more brittle and more susceptible to fracture. Furthermore, the bitumen polymer modification showed a relatively small change in the recovery behaviour compared to plain bitumen, which was also observed by Kim and Roque (2006). Therefore, the results from Shen and Carpenter (2007) and Qiu (2012) could not be confirmed.

Concerning the other influencing factors, the increase of bitumen content in asphalt mixture by 0.5 % shows best recovery characteristics. This can be explained by higher flow processes of the bituminous mastic film that positively influences closing of the initiated micro cracks. The degree of compaction used in this investigation seems to have no significant influence on material ability to restore its initial properties. Furthermore, the recovery potential increases with the increase of the rest period duration.

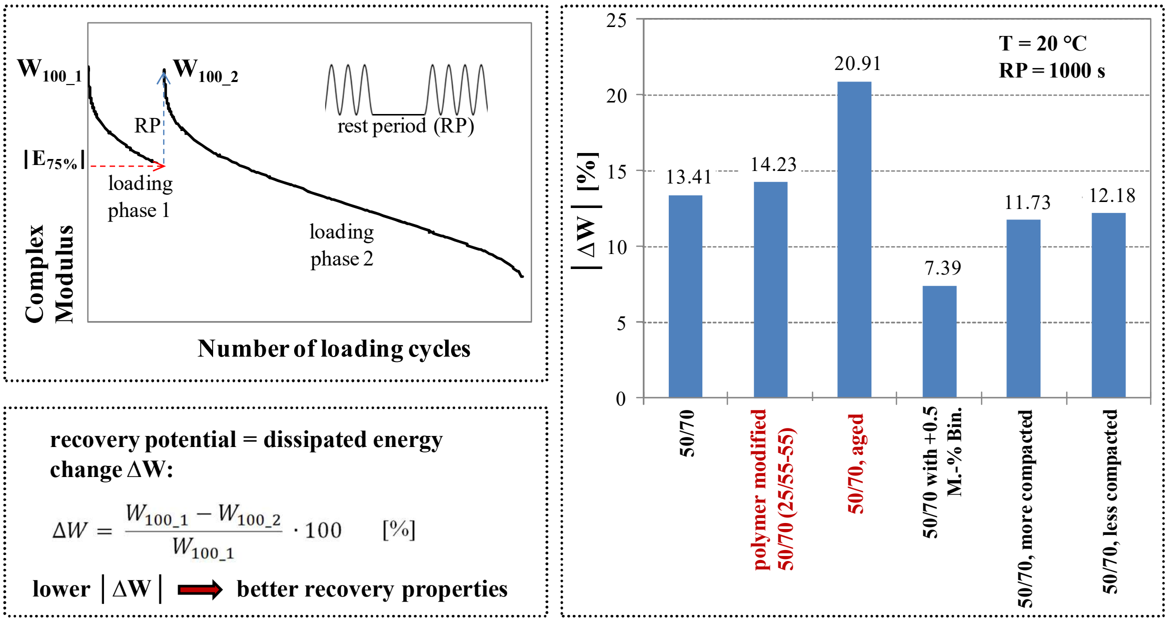


Figure 26. Test protocol used to characterize asphalt mixture recovery capacity (left, top); procedure for evaluation of the recovery potential (left, bottom); recovery potential of asphalt mixtures determined by the relative change in dissipated energy for some influencing parameters in tests with 1000 s rest period (right).

Publication D aims in developing a new procedure/new recovery index for laboratory evaluation of asphalt mixtures recovery properties, able to mitigate the material-related scatter observed in the experimental results. For that purpose, laboratory investigation relying on dissipated energy approach is employed. The procedure is based on continuous fatigue tests and discontinuous fatigue tests with a single rest period, performed using the uniaxial tension-compression test apparatus in controlled-stress mode.

The principle of deriving the new recovery index is presented in Figure 27. The procedure excludes material-related scatter in continuous tests, which are used as a basis for the recovery calculation (see Figure 27, left, top). This is achieved by using a unique normalized energy ratio-complex modulus curve (Figure 27, right, top), that follows almost the same trend for all conducted continuous fatigue tests, no matter how many loading cycles the asphalt specimen experiences at failure. Therefore, it is hypothesized that a unique trend can be assumed for all tests conducted at the same loading conditions. Using a so-derived representative fatigue curve it is possible to estimate with good approximation the maximum value of the energy ratio (ER_{100}) for the extended first loading phase of discontinuous test (cp. dashed red line in Figure 27, left, bottom), that can be represented as the continuous fatigue test, performed at same loading conditions. This represents the key part of the new recovery index that compares maximum energy ratio from test with rest period ($ER^{RP}{}_{100}$) with the calculated energy ratio from continuous tests (ER_{100}), obtained from the same asphalt mixture specimen (cp. Figure 27, left, bottom).

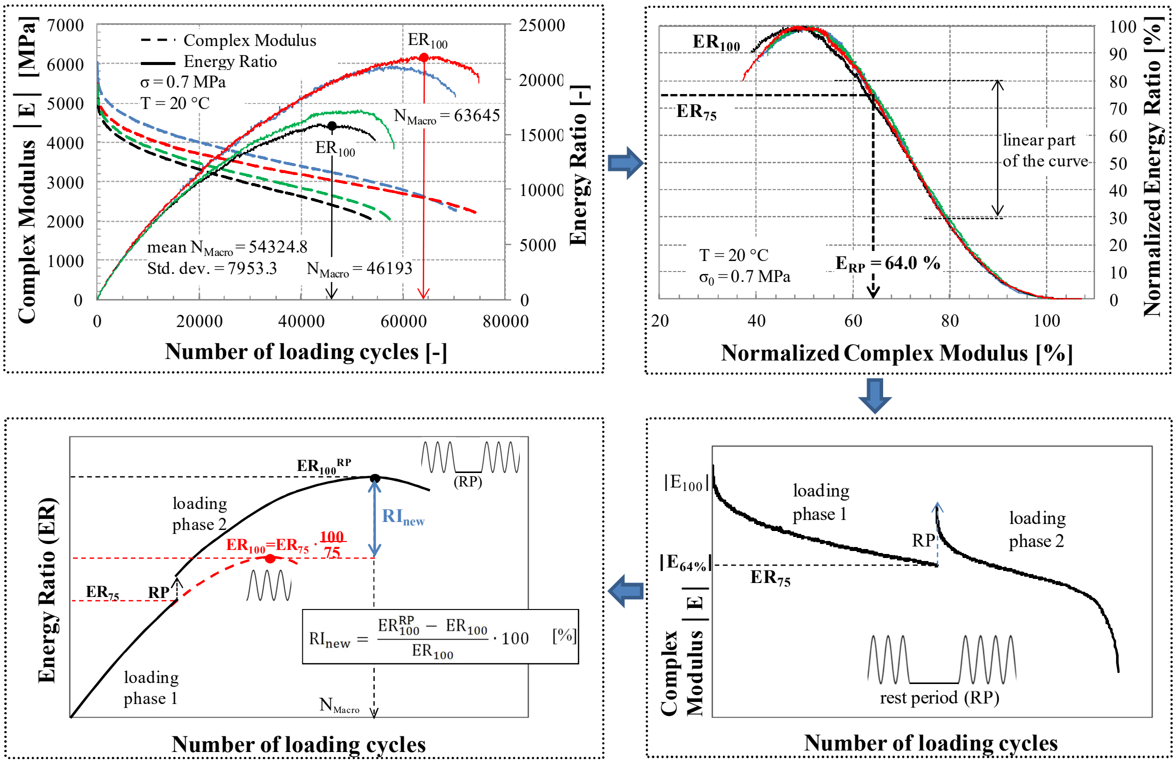


Figure 27. Principle of deriving the new recovery index. Evolutions of complex modulus and energy ratio in function of number of loading cycles in continuous uniaxial tension-compression fatigue tests (left, top); corresponding evolutions of normalized energy ratio-complex modulus curves (right, top); test protocol used to study the recovery potential (schematic) (right, bottom); procedure of estimating the new recovery index (schematic) (left, bottom).

Validation of the new recovery index, performed introducing different durations of rest period in the test procedure, shows that the recovery index increases as the rest time increases, allowing for a plausible assessment of the recovery properties (see Figure 28, left). The result scattering is significantly reduced, indicating good test repeatability. On the contrary, the recovery index that compares the responses of continuous and discontinuous fatigue tests based on the number of loading cycles at fatigue failure (cp. Little et al., 2001; Santagata et al., 2009, see Equation in Figure 28, right) does not show any reliable dependence from rest period duration for the same test data (cp. Figure 28, right). Based on these findings, the developed recovery index can be seen as an appropriate tool for the plausible evaluation of asphalt mixture recovery properties.

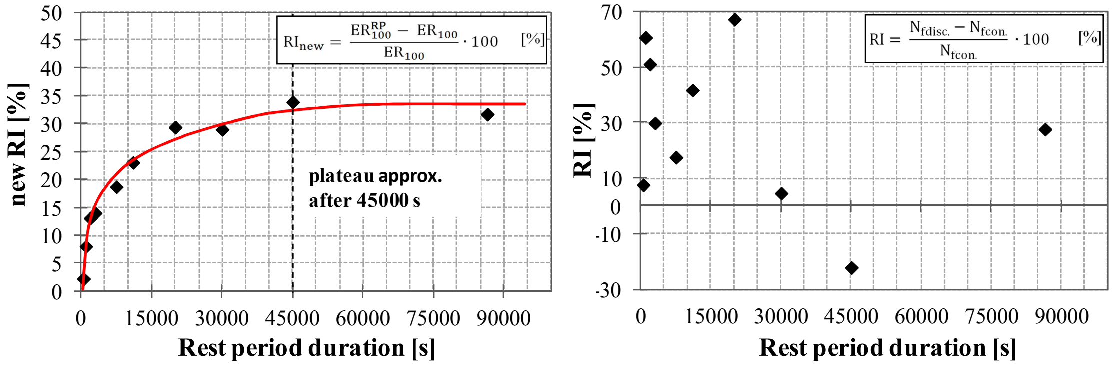


Figure 28. New recovery index (left) and recovery index that compares the responses of continuous and discontinuous fatigue tests based on the number of loading cycles at fatigue failure (cp. Little et al., 2001; Santagata et al., 2009) (right), dependent on rest period duration.

Publication E aims in investigating the asphalt mixture recovery properties in detail, where rest period duration dependency is studied taking into consideration nonlinearity and self-heating effects observed during cyclic loading. For this purpose, laboratory investigation based on uniaxial tension-compression test in stress controlled mode is employed, considering amplitude sweep tests, temperature sweep tests, and discontinuous fatigue tests with single rest periods of different durations.

The recovery evaluation is based on observing the total complex modulus recovery during the rest period of discontinuous fatigue test (cp. Figure 29, left, top), where the influence of nonlinearity and self-heating effects on this recovery is quantified.

In order to examine the influence of self-heating on recovery properties, a new methodology is introduced, allowing embedding a small-size temperature sensor in the asphalt specimen during compaction of the asphalt mixture. In such a way, efficient sensor integration can be achieved, providing a consistent continuity of the material within the specimen and limiting distortion of the stress field. This procedure avoids the introduction of a point of weakness in the specimen, as it is usually the case, when the sensor is placed after compaction by drilling a hole in the specimen.

The research results indicate that the effect of nonlinearity on the complex modulus recovery is not affected by increased rest period duration (see Figure 29, left, bottom), and is relatively low (8.5 %) compared to the influence of other effects. On the contrary, the effect of temperature variation in the core of the specimen occurring during cyclic excitation and during rest periods (self-heating), on complex modulus recovery is highly affected by the rest period duration (see Figure 29, right, top) and can account up to 17.1 % of the overall complex modulus recovery. However, by subtracting the effects of nonlinearity and self-heating from the total recovery, it is evident that the joint action of further effects such as thixotropy, self-healing, and strain relaxation (for stress controlled test only) mainly influences the complex modulus recovery during the rest period (see Figure 29, right, bottom), with 74.4 % for rest periods longer than 15000 seconds. Nevertheless, the effects of nonlinearity and self-heating cannot be neglected.

Furthermore, it was shown that for short rest period durations, the effect of self-heating contributes more rapidly to complex modulus recovery than other biasing effects, such as thixotropy, self-healing and strain relaxation. This effect vanishes when temperature reaches its original value (after 2500 seconds in this experiment), leaving to other biasing phenomena dominant in term of complex modulus recovery.

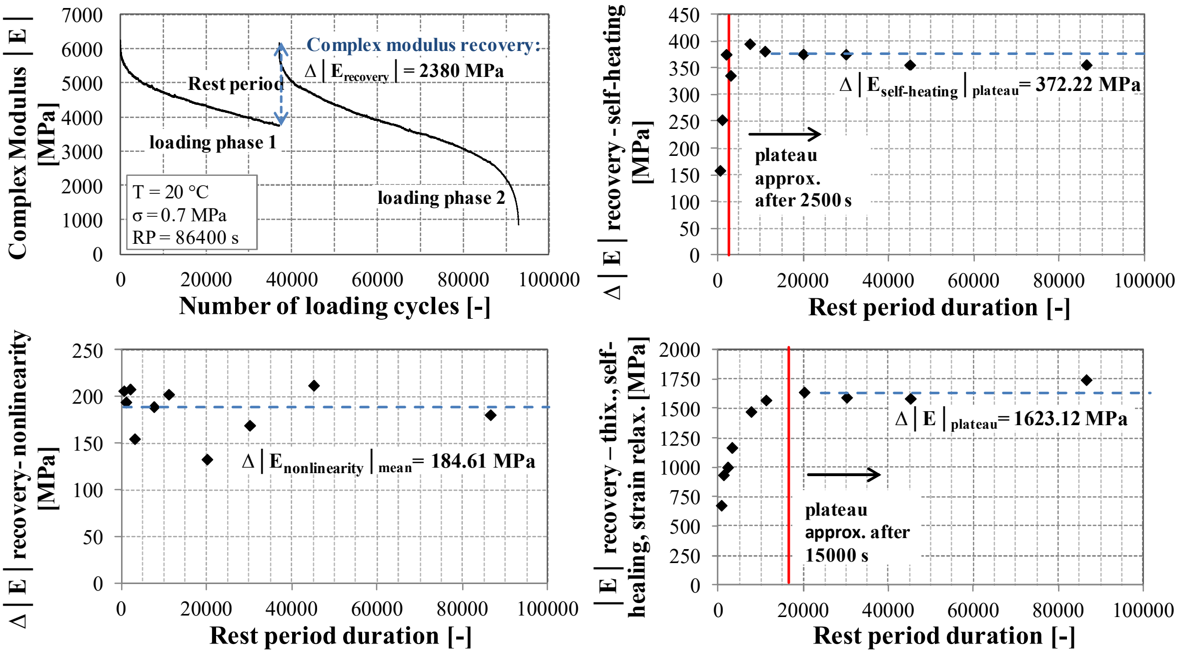


Figure 29. Total recovery of the absolute value of complex modulus in discontinuous fatigue test with single rest period of 86400 seconds (left, top); recovery of the absolute value of complex modulus for different rest period durations as a consequence of: self-heating effect (right, top), nonlinearity effect (left, bottom), thixotropy, self-healing and strain relaxation effects (right, bottom).

Publication F aims in clarifying the question if the existing cyclic shear test apparatus introduced by Wellner and Ascher (2007) for testing stiffness can also be used for fatigue evaluation of asphalt mixture layers' interface. In order to determine the influence of different test and material parameters on fatigue behaviour of layers' interface and to find the optimum test parameters for fatigue evaluation, a comprehensive investigation is performed using continuous fatigue tests.

The cyclic shear test apparatus introduced by Wellner and Ascher (2007) is based on direct shear testing, where the interface of double-layered asphalt sample is exposed to sinusoidal cyclic loading in displacement (strain) controlled mode (see Figure 30, left, top). In addition to the cyclic shear load, a compressive static normal stress can be applied. Both normal stress and temperature are varied on a set of bond types, differing in asphalt mixture type, tack coat type, and tack coat application rate.

As a result of the continuous cyclic loading in shear fatigue test, the interface shear stiffness decreases gradually, and is highly dependent on the normal stress application (see Figure 30, right, top). For tests with normal stress, the shear stiffness does not exhibit three-stage evolution, since no rapid failure of the layers' interface occurs. This is a direct consequence of the applied normal stress, which through its confining action makes the effects of friction, adhesion and interlock much more effective.

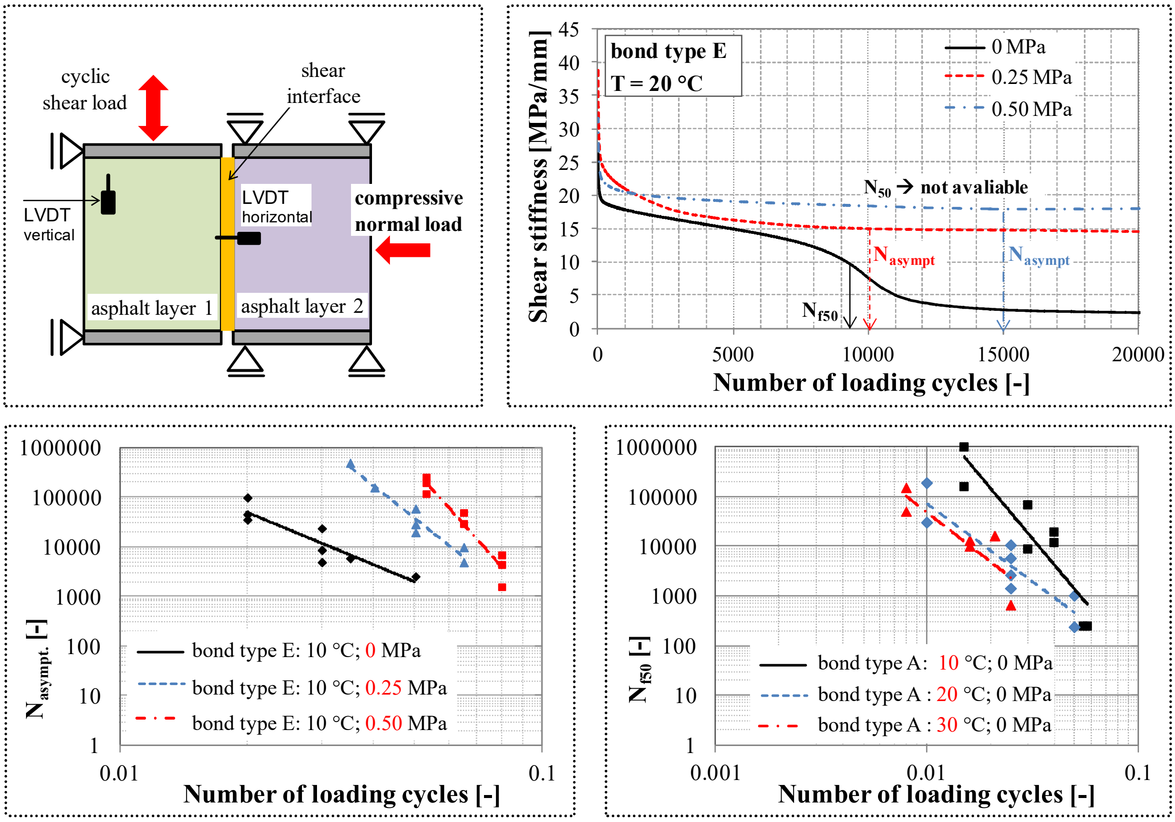


Figure 30. Schematic representation of the cyclic shear apparatus introduced by Wellner and Ascher (2007) (left, top); evolution of the interface shear stiffness over the number of loading cycles for fatigue tests at 20 °C and at three normal stress levels (right, top); fatigue functions at 10 °C, depending on normal stress level (left, bottom); fatigue functions without normal stress application (0 MPa), depending on test temperature (right, bottom).

If conducting the continuous fatigue tests at three different displacement amplitudes with three test replicates, a unique fatigue function for each asphalt mixture layers' interface is identified (see Figure 30, bottom). Increased displacement amplitude leads to a shorter fatigue life of the layers' interface.

The research results indicate that bond fatigue properties are highly dependent on the normal stress application, and increase as the normal stress increases (see Figure 30, left, bottom). This is due to enhanced friction, adhesion and interlock at the shear interface. Nevertheless, the induced compressive normal load can cause accumulation of the permanent deformation at the layers' interface. This makes the fatigue evaluation even more difficult, since the permanent deformation accumulation can provoke shear stiffness increase.

Furthermore, due to the different bond viscosities at the selected testing temperatures, the interface shear stiffness shows a remarkable high dependency, where decreased temperatures lead to increased interface shear stiffness (see Figure 30, right, bottom). Independent on the normal stress level, the fatigue tests at 10 °C show for most bond types the best fatigue results.

Based on the comprehensive laboratory investigation, the analysis performed for finding the optimal test parameters indicates that the shear tests conducted at 20 °C and without normal stress application can be successfully used for fatigue evaluation of asphalt mixture layers' interface as a first approximation. However, temperature dependency of fatigue also needs to be investigated for interlayer bonding.

Publication G aims in clarifying the question if the shear strength obtained from monotonic shear tests can be used as an indicator for the long-term interface shear performance, as observed under cycling loading. For that purpose, the comparison between results from the proposed cyclic shear fatigue procedure with optimal test parameters (cp. Publication F) and results from monotonic shear test (Leutner, 1979) is performed, using a set of bond types differing in the asphalt mixture type, tack coat type, tack coat application rate, and laboratory preparation of asphalt specimens.

In order to allow reliable comparison between monotonic and cyclic shear tests used, the number of loading cycles at failure $N_f = 10000$ in cyclic tests is selected, where the corresponding displacement amplitudes are calculated for each bond type. Based on resulting shear strengths from monotonic shear tests (lower shear strength implies lower interface bonding), and based on the calculated displacement amplitudes at $N_f = 10000$ from cyclic shear fatigue tests (lower displacement amplitude implies lower interface bonding), the considered bond types can be ranked with respect to interface shear bonding properties (see Figure 31).

According to the best practice and research experience the cyclic shear fatigue testing leads to the expected bond type ranking. However, the resulting shear strength from monotonic shear test cannot reflect the research and practice experience for bond materials used in this research in total, because differences in bond types with some specific material and production variations cannot be recognized (cp. Figure 31). Therefore, shear strength from monotonic shear test can be used only as a rough indicator for the long term interface bonding performance.

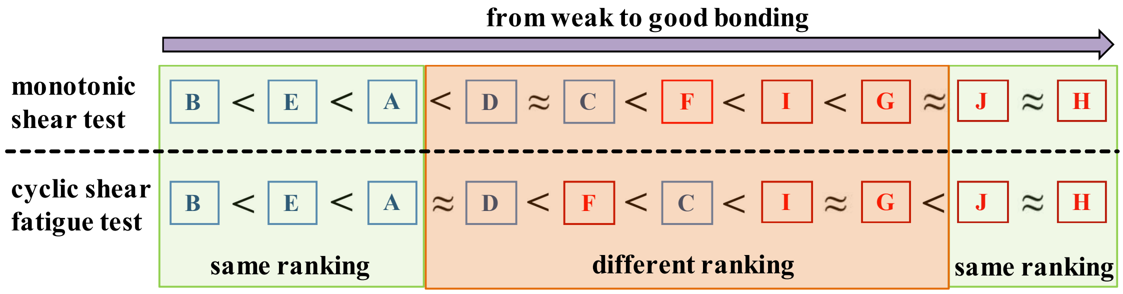


Figure 31. Bond type ranking in monotonic shear test (based on resulting shear strengths), and in cyclic shear test (based on calculated displacement amplitudes at N_{50} = 10000).

3.3 Perspectives

Based on the work presented in the papers, it is obvious that an appropriate evaluation of the fatigue and recovery properties is a quite difficult task, requiring a good insight into material response during cyclic loading and during rest. Particularly, it is important to choose an optimal test apparatus, able to appropriately address performance properties; as shown in this thesis a test without accumulation of permanent deformation is highly recommended for fatigue and recovery evaluation.

Beside the significance of choosing an appropriate test configuration, the selection of the test temperature for fatigue evaluation plays an important role. As shown in this thesis, a fatigue procedure based on a punctual fatigue assessment at a single temperature, although in best accordance with the European Standard, can lead to misleading fatigue evaluation. Therefore, the new test protocol introduced represents a good alternative to conventional testing, since relying on extended temperature range allows for a plausible evaluation of asphalt mixture fatigue properties. Therefore, further work is needed for validation purposes, using wider variety of different asphalt mixtures.

Concerning the asphalt recovery properties, additional research is needed in order to discriminate the specific biasing effects which drive the material recovery during rest periods and to examine ‘‘pure’’ self-healing properties. Since effects of nonlinearity and self-heating could be relatively straightforward unraveled, further investigations on understanding the thixotropy phenomenon during cyclic loading are necessary. For evaluation of self-heating effects, it is highly recommended to apply the described procedure for embedding the small-size temperature sensor into asphalt mixture during compaction, since this procedure limits potential distortion of the asphalt microstructure and provides a consistent continuity of the material within the specimen.

Within the selective unraveling process of biasing phenomena, better interpretation of the cyclic fatigue tests could be provided. Consequently, a ‘‘real’’ damage leading to the failure of asphalt mixtures could be examined for each type of fatigue test. Coupling the effects of ‘‘pure’’ self-healing and ‘‘real’’ damage, better correlation between laboratory tests and performance in-situ is guaranteed, allowing more precise prediction of the pavement’s service life.

Concerning the asphalt mixture layers’ interface bonding properties, a promising procedure was introduced for evaluation of fatigue (debonding) properties. The results reflect research and practice experience. Nevertheless, further work is needed in order to improve test repeatability. The shear gap of 1 mm does not seem to be most appropriate, especially when mixtures with high nominal maximum aggregate size are used. Moreover, temperature dependency of interlayer fatigue properties needs to be studied. Since shear fatigue test requests extended laboratory effort compared to monotonic shear test, it is not recommended to use it on a routine basis, as long as differentiating between specific bond materials in monotonic shear test is assured.

4 Publications

Publication A: Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015. Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests. Proc., 8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials, Oct. 7-9, 2015, Ancona, Italy, Vol. 11, RILEM Bookseries, pp. 693-709, DOI: 10.1007/978-94-017-7342-3_56, Springer.

Publication B: Isailović, I., and Wistuba, M. 2018. Sweep test protocol for fatigue evaluation of asphalt mixtures. Journal of Road Materials and Pavement Design, pp. 1-14, DOI: 10.1080/14680629.2018.1438305, Taylor and Francis.

Publication C: Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Investigation on mixture recovery properties in fatigue tests. Journal of Road Materials and Pavement Design, pp. 1-11, DOI: 10.1080/14680629.2017.1300598, Taylor and Francis.

Publication D: Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Experimental study on asphalt mixture recovery. Journal of Materials and Structures, Vol. 50:196, pp. 1-9, DOI: 10.1617/s11527-017-1064-0, Springer.

Publication E: Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Influence of rest period on asphalt recovery considering nonlinearity and self-heating. Journal of Construction and Building Materials, Vol. 140, pp. 321-327, DOI: 10.1016/j.conbuildmat.2017.02.122, Elsevier.

Publication F: Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2017. Fatigue investigation on asphalt mixture layers' interface. Journal of Road Materials and Pavement Design, Vol. 18, sup4, pp. 514-534, DOI: 10.1080/14680629.2017.1389087, Taylor and Francis.

Publication G: Isailović, I., and Wistuba, M. 2018. Asphalt mixture layers' interface bonding properties under monotonic and cyclic loading. Journal of Construction and Building Materials, Vol. 168, pp. 590-597, DOI: 10.1016/j.conbuildmat.2018.02.149, Elsevier.

A Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests[1]

Abstract: During cyclic fatigue testing of asphalt mixture specimens under stress control, a continuous change of the strain amplitude is observed in each loading cycle either under pure tensile or under tensile-compressive stress conditions. Depending on the type of the applied load and on the specific viscoelastic behavior of the asphalt mixtures this strain change can dramatically vary in association with a change in various mechanical properties. In order to study the variation of mechanical properties during cyclic fatigue tests under stress control an experimental program was performed using an approach based on dissipated energy. This study considers the following stress-controlled fatigue tests: indirect tensile test, uniaxial tension test and uniaxial tension-compression test. The hysteresis loops are drawn, and the dissipated energy is calculated. Based on the similar number of loading repetitions at failure, the tests are comparatively analyzed, and the changes in mechanical properties are identified. As a result, the tension-compression test shows low permanent deformation and high variation of dissipated energy which can be attributed to a distinct change in the material's mechanical properties. On the other hand, the uniaxial tension test and indirect tensile test exhibit high accumulation of permanent deformation with very few changes in mechanical properties during cyclic excitation. Based on these results the uniaxial tension test and the indirect tensile test in stress control are not well-suited for fatigue analysis since failure most likely occurs by accumulation of permanent deformation.

Keywords: dissipated energy, hysteresis loop, mechanical properties, permanent deformation.

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[1] Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015. Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests. Published in Proc., 8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials, Oct. 7-9, 2015, Ancona, Italy, Vol. 11, RILEM Bookseries, pp. 693-709, DOI: 10.1007/978-94-017-7342-3_56, Springer.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 85 %

A.1 Introduction

Fatigue is a major distress that leads to early failure of pavement materials. It results in material cracking under the effect of repeated loading. Even though the individual load is lower than the material's ultimate strength, due to the gradual increase in the load repetitions, micro cracks initiate and accumulate, coalescing into macro cracks that finally lead to failure (Dowling, 1999).

Fatigue properties of asphalt mixtures are generally determined using different laboratory tests under different loading modes: uniaxial, indirect, bending, in tension, compression or both (cp. EN 12697-24). Conventionally two loading modes are used: constant stress control for relatively thick pavements and constant strain control for relatively thin flexible pavements (Ghuzlan and Carpenter, 1999).

Especially as regards test methods with dominant tensile loading (e.g. the indirect tensile test), depending on the type of binder, its rheological properties and aggregate gradation used, these tests can generate a substantial plastic (irreversible) strain as a consequence of material viscoelastic properties under tensile load. According to the work of Di Benedetto et al. (2004) the irreversible accumulated strain in fatigue tests can hide the effects associated to fatigue which is quite detrimental for analysis purposes. Consequently failure occurs probably by accumulation of permanent strain (Di Benedetto, 2013).

A laboratory analysis was therefore performed in order to observe the evolution of the material mechanical properties and of the permanent deformation during indirect tensile fatigue test (ITT). Uniaxial tension test (UTT) and uniaxial tension-compression test (UTCT) in stress control were also used in this investigation for the purpose of employing different specimen geometries and loading conditions. The analysis of the mechanical properties evolution was performed using the dissipated energy approach that is a fundamental instrument for observing the difference in material behavior during cyclic loading (Carpenter and Shen, 2006).

A.2 Experimental study

A.2.1 Material composition

The experimental investigation was carried out using an asphalt mixture for surface course, i.e. asphalt concrete of the type AC 11 D S for highest road category prepared with aggregates having maximum grain size of 11 mm and with a bitumen with penetration grade 50/70 (acc. to EN 1426) in percentage of 5.9 % by total mixture weight. Figure A.1 represents the aggregate gradation curve. The tested specimens had an air voids content of 2.5 %.

Figure A.1. Aggregate gradation curve used to prepare asphalt mixture specimens.

Test specimens were cut from slabs made with a segmented steel roller compactor. Using this compaction device it is possible to produce asphalt mixture slabs with adequate mechanical characteristics compared to those in the field (Renken, 2000). The compactor uses a steel roller cylindrical sector to produce a kneading action and a downward force to the specimen in both pre-compaction and main compaction phase (Wistuba, 2014). The pre-compaction is displacement controlled and simulates the compaction effort of paver, and main compaction is force controlled and simulates the effective compaction by roller compactors in the field. Each phase consists of 12 roller passes.

A.2.2 Fatigue analysis

Fatigue analysis of the selected asphalt mixture was performed using three different fatigue tests: indirect tensile test (ITT), uniaxial tension test (UTT) and uniaxial tension-compression test (UTCT). In ITT test a vertical acting compressive stress induces in the specimen a non-homogeneous stress state, where in the middle portion of the specimen a horizontal tensile stress is observed (Figure A.2). This tensile horizontal stress leads primarily to the specimen failure. In opposite to ITT test, in UTT and UTCT constant stress and strain fields are imposed.

A sinusoidal cyclic stress was selected under load control mode at a frequency of 10 Hz and at a test temperature of 20 °C. The amplitudes were chosen through a pre-testing procedure in such a way that the different types of tests give similar fatigue lives (number of loading cycles at failure). As a result the following stress amplitudes were chosen:

- ITT: induced horizontal stress amplitude = 0.133 MPa,
- UTT: axial stress amplitude = 0.18 MPa,
- UTCT: axial stress amplitude = 1.05 MPa.

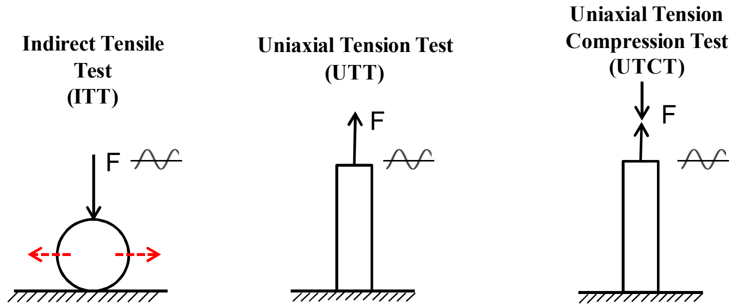


Figure A.2. Principles of the indirect tensile test (left), uniaxial tension test (middle) and uniaxial tension compression test (right).

The most important parameters for material analysis were monitored and recorded during the entire tests duration. For the evaluation of the number of loading repetitions at failure the energy ratio (*ER*) approach proposed by Hopman et al. (1989) was used. *ER* represents the ratio between the initial dissipated energy, to the dissipated energy at cycle *n*, multiplied by the load cycle value *n*:

$$ER_n = \frac{n \cdot W_0}{W_n} \quad [\text{-}], \tag{A.1}$$

where: n = cycle number [-], W_0 = initial dissipated energy (for 100[th] cycle) [kJ/m³], W_n = dissipated energy at cycle n [kJ/m³].

A typical example of the energy ratio evolution is shown in Figure A.3.

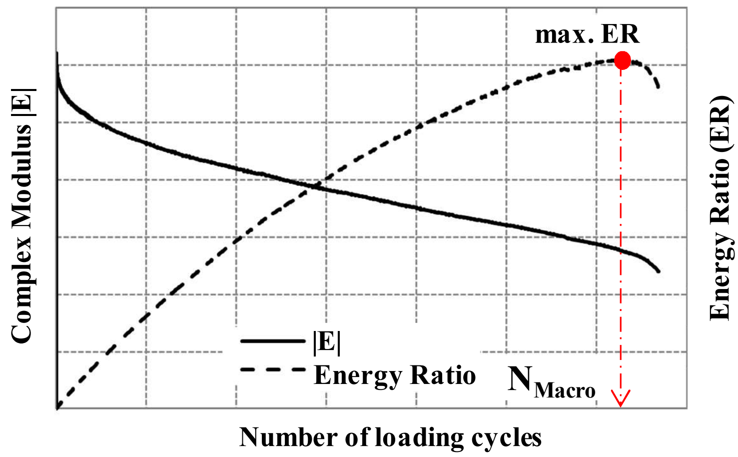


Figure A.3. Typical evolution of the complex modulus and of the energy ratio over the number of loading cycles in a uniaxial tension-compression fatigue test.

By plotting *ER* versus the number of loading cycles, fatigue life is defined as the number of loading cycles for which *ER* achieves the maximum. The so-obtained point represents the transition between micro and macro cracking and is specified as N_{Macro}.

A.2.3 Analysis of change in mechanical properties using dissipated energy approach

The energy dissipated within one loading cycle represents the difference between the energy provided to the material during the loading phase and the energy released during unloading. If a material is perfectly elastic, the loading and unloading curves follow the same paths, meaning that all the energy is recovered, without any energy dissipation (Figure A.4, left). In case of viscoelastic materials such as asphalt loading and unloading curves do not overlap, which indicates loss of energy within the material. Part of the energy is dissipated from the system through external work, heating or damage (Ghuzlan and Carpenter, 2000).

The ellipse generated by the loading and unloading phases is called hysteresis loop and its area corresponds to the energy dissipated in one loading-unloading cycle (Figure A.4, right). For the calculation of dissipated energy (W_n) in one loading cycle the following equation can be used:

$$W_n = \pi \cdot \sigma_n \cdot \varepsilon_n \cdot sin\varphi_n \quad [\mathrm{kJ/m^3}], \qquad (A.2)$$

where: σ_n = stress amplitude at cycle n [MPa], ε_n = strain amplitude at cycle n [‰], φ_n = phase angle at cycle n [°].

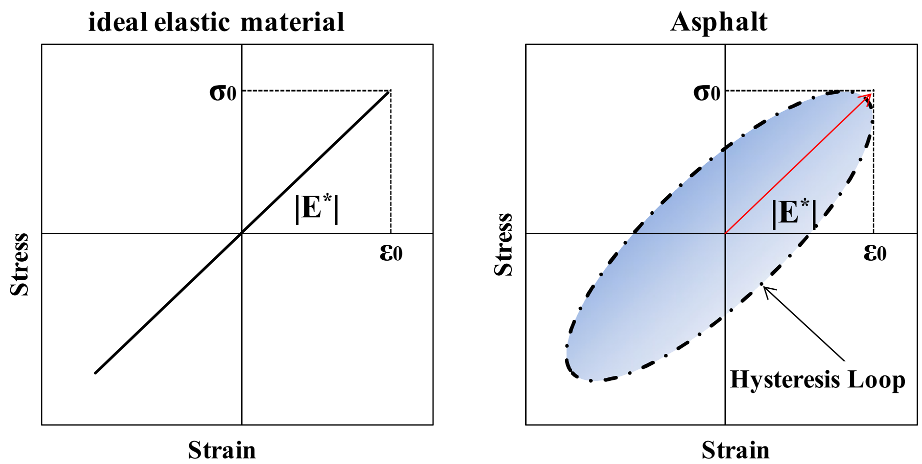


Figure A.4. Loading cycle in a strain-stress diagram for a perfectly elastic material (left), and for a viscoelastic material, such as asphalt (right).

The dissipated energy can be used for investigating the change in mechanical properties during fatigue tests, since it considers variations both in the phase angle and in the strain or stress state (depending on the loading mode) during the material damage evolution. In stress controlled fatigue test the dissipated energy increases while it decreases in strain controlled mode.

Based on the work of Di Benedetto (2013) the material behavior in a cyclic test can be characterized by the change of the form and position of the hysteresis loop in each loading cycle. Rotation and expansion of the hysteresis loops with increasing number of loading cycles is primarily due to material fatigue (or effects associated with fatigue) (Figure A.5, left), while horizontal shifting along the strain axis can be interpreted as a permanent deformation of the specimen (Figure A.5, right). On this basis, the evaluation of the mechanical properties during fatigue tests can be performed.

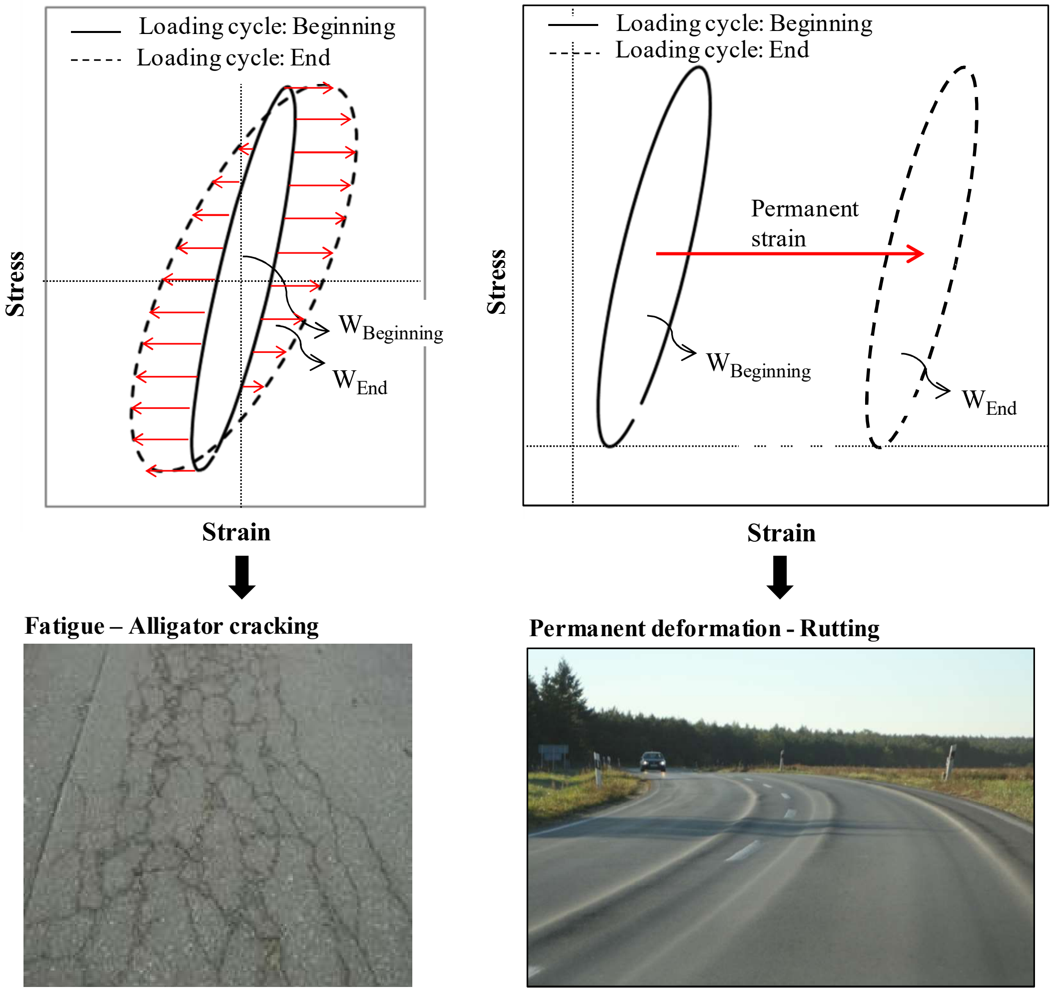
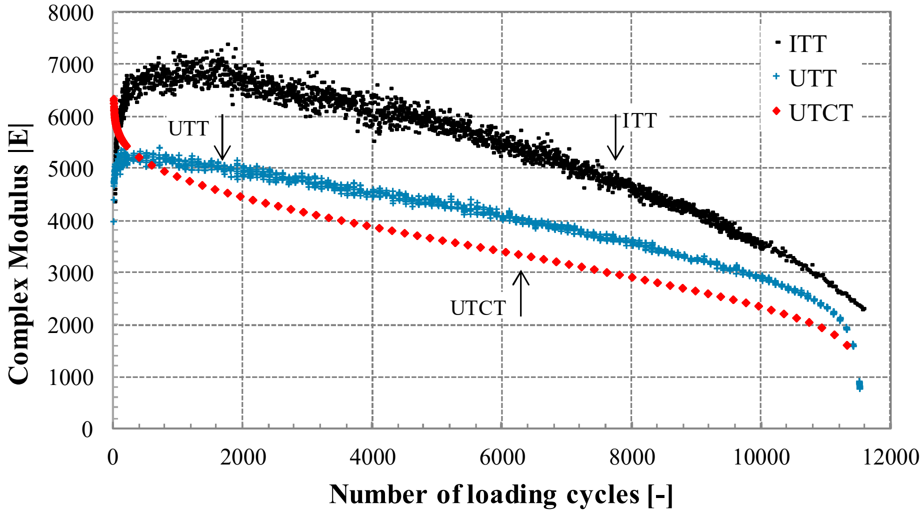


Figure A.5. Interpretation of a fatigue test (left) and a permanent deformation test (right); Hysteresis loops for the loading cycles at the beginning and at the end of the test (cf. Di Benedetto, 2013).

A.3 Test results and analysis

The change in mechanical properties is evaluated in three different fatigue tests with similar fatigue life durations. Using the *ER* proposed by Hopman, the following numbers of loading repetitions at failure (N_{Macro}) were achieved (see Figure A.6):

- Indirect tensile test (ITT): 8650 cycles,
- Uniaxial tension test (UTT): 8501 cycles,
- Uniaxial tension-compression test (UTCT): 8580 cycles.



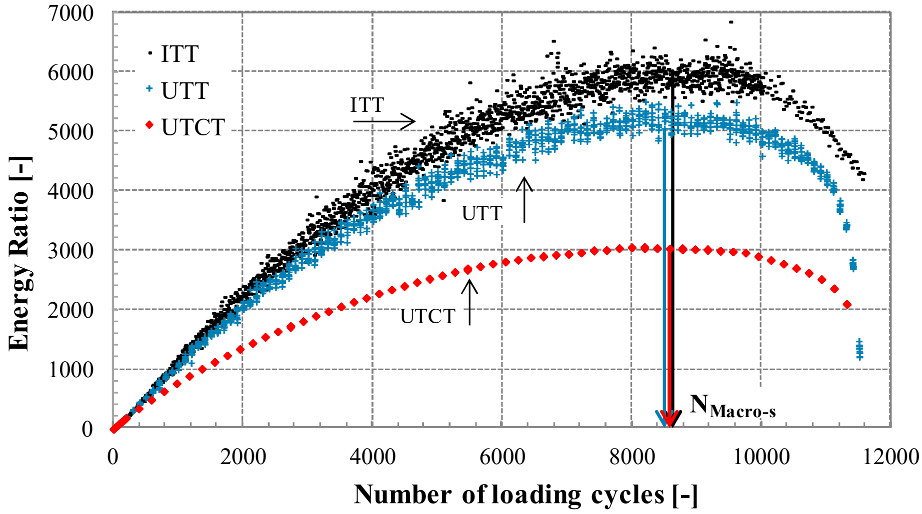


Figure A.6. Evolution of absolute value of complex modulus and energy ratio over the number of loading cycles and achieved $N_{Macro-s}$ in indirect tensile test (ITT), uniaxial tension test (UTT) and uniaxial tension-compression test (UTCT).

Based on the almost same number of loading repetitions at failure it is possible to conduct a reasonable comparison between these three tests by determining the individual changes in mechanical properties. As reported by Di Benedetto (2013) the change in asphalt mixture mechanical properties in a fatigue test can be characterized by the change of the hysteresis loop form during cyclic loading, which directly corresponds to the change in dissipated energy. For this reason the hysteresis loops at the beginning of the test (at cycle 100) and at failure (for N_{Macro}) are drawn and dissipated energy change between these loading cycles is comparatively calculated for each type of fatigue test performed. The test results are plotted in Figure A.7 and Figure A.8.

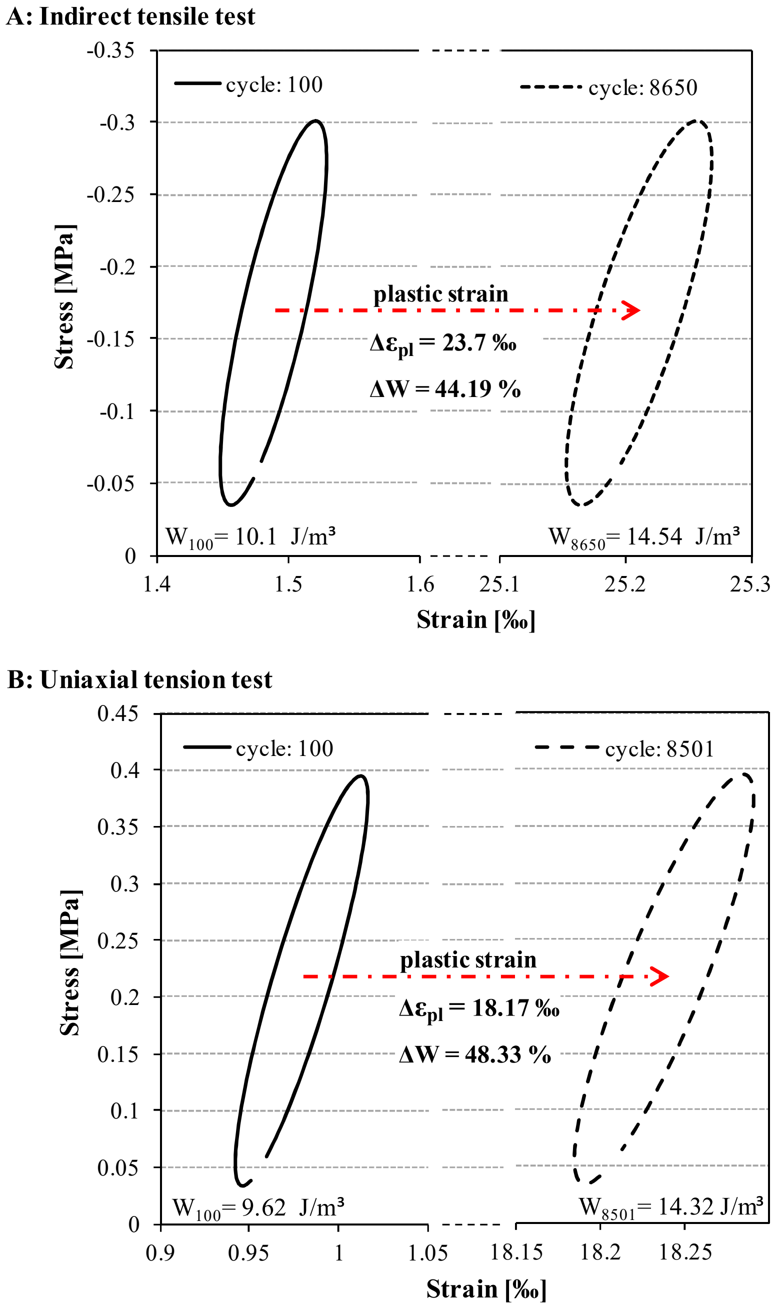


Figure A.7. Hysteresis loops at cycle 100 and at failure (cycle N_{Macro}) for indirect tensile test (A) and uniaxial tension test (B).

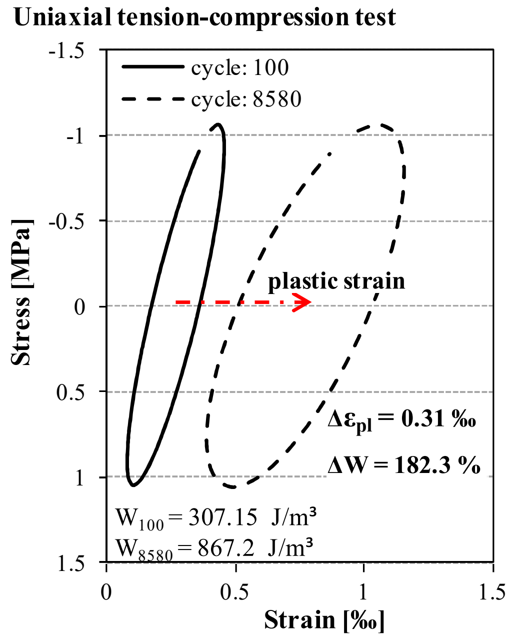


Figure A.8. Hysteresis loops at cycle 100 and at failure (cycle N_{Macro}) for uniaxial tension-compression test.

The test results show that testing procedures including only tensile stress condition such as in ITT and UTT lead to relatively slow increase in dissipated energy (ΔW) between the beginning of the testes and failure, with 44.19 % and 48.33 % respectively. The hysteresis loops represented in Figure A.7 show relatively small change in shape with significant horizontal shifting associated to plastic deformation, which in ITT test exceed 23 ‰.

On the other hand the UTCT shows a distinct change in the shape of the hysteresis loop with 182.3 % growth of dissipated energy at failure (Figure A.8). The plastic strain of UTCT is smaller compared to ITT and UTT tests (0.31 ‰) and can be assumed as negligible.

The higher dissipated energy change observed in the stress controlled tension-compression test compared to the other tests is a consequence of the significant increase of elastic strain amplitude and phase angle as loading repetitions increase. This implies that the material is experiencing higher loss in stiffness and delayed response over time with respect to ITT and UTT. This is associated to remarkable change in mechanical properties.

Generation of large plastic deformation in ITT and UTT is a consequence of stress conditions coupled with material's rheological characteristics. If only tensile stress acts in the specimen and material viscosity is low it will result in additional plastic deformation in each loading cycle. On the other hand in UTCT the compressive stress part in each loading cycle develops inverse plastic deformation (partially or entirely) and prevents the evolution of disproportional permanent deformation.

A.4 Summary

In this study, a dissipated energy approach is applied to investigate the change of mechanical properties in three stress controlled fatigue tests: indirect tensile test, uniaxial tension test and uniaxial tension-compression test. Based on the almost same number of loading repetitions at failure it was possible to conduct a reasonable comparison between these three tests.

The test results show that indirect tensile test and uniaxial tension test present comparatively little change in the material mechanical properties, with high accumulation of plastic deformation. On the other hand the uniaxial tension-compression test shows significant change in mechanical properties (approx. four times higher), with minimal plastic deformation.

According to the test results, it can be concluded that indirect tensile test and uniaxial tension test are not appropriate tests for fatigue analysis, because the failure is primarily associated to the accumulation of permanent deformation, and not in consequence of fatigue damage.

More research on this field is needed in order to examine the change of mechanical properties more in detail by unraveling the effects of thixotropy and material heating during cyclic loading.

A.5 References

Carpenter, S., and Shen, S. 2006. A dissipated energy approach to study HMA healing in fatigue. In Transportation Research Record (TRR): Journal of the Transportation Research Board, No 1970, pp. 178-185.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundström, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Di Benedetto, H. 2013. Fatigue and other phenomena during cyclic loading of bituminous materials. Keynote at Int. EATA Conf., Jun. 3-5, 2013, Braunschweig, Germany.

Dowling, N. E. 1999. Mechanical behavior of materials, engineering methods for deformation, fracture, and fatigue. Second Edition. Prentice Hall, Upper Saddle River, New Jersey.

EN 12697-24. 2012. Test methods for hot mix asphalt - Part 24: Resistance to fatigue. European Standard.

EN 1426. 2013. Bitumen and bituminous binders - Determination of needle penetration. European Standard.

Ghuzlan, K., and Carpenter, S. 2000. An energy-derived, damage-based failure criteria for fatigue testing. Transportation Research Record, Journal of the Transportation Research Board, No. 1723, pp. 141-149.

Hopman, P., Kunst, P., and Pronk, A. 1989. A renewed interpretation model for fatigue measurement. verification of Miner´s rule. Proc., 4th Eurobitumen Symposium, Oct. 4-6, 1989, Madrid.

Renken, P. 2000. Influence of specimen preparation onto the mechanical behaviour of asphalt aggregate mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, pp. 729-735, Sept. 20-22, 2000, Barcelona, Spain.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

B Sweep test protocol for fatigue evaluation of asphalt mixtures[2]

Abstract: This paper presents a laboratory test protocol for evaluating fatigue properties of asphalt mixtures through sweep tests at multiple amplitudes and frequencies. Conventional fatigue evaluation of asphalt mixtures typically relies on a limited number of single fatigue tests, and each test is performed at constant test temperature. Moreover, in order to reduce laboratory effort to a minimum, testing is quite often limited to a single test temperature, which means that the dependency of asphalt fatigue on temperature is ignored. Such test procedure is in best accordance with the European Standards. However, so-derived results may provoke misleading conclusions, as exemplarily shown in this study. In order to solve this shortcoming, a sweep test protocol for fatigue evaluation of asphalt mixtures at different temperatures is proposed. Frequency-amplitude sweeps are used for complex modulus evaluation and fatigue evaluation, but without significantly extending the laboratory effort compared to conventional fatigue testing. This sweep test protocol is applicable for fatigue evaluation of any asphalt mixture.

Keywords: fatigue testing, fatigue performance, multi-stage test, frequency sweep, amplitude sweep.

[2] Isailović, I., and Wistuba, M. 2018. Sweep test protocol for fatigue evaluation of asphalt mixtures. Published in Journal of Road Materials and Pavement Design, pp. 1-14, DOI: 10.1080/14680629.2018.1438305, Taylor and Francis.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 85 %

B.1 Introduction

Bitumen composition is primarily driven by the cocktail of hydrocarbons originating from the crude oil, which shows a rheologically complex viscous behaviour. If bitumen is stressed, the elastic and plastic shares of deformation under load are highly dependent on temperature and load frequency. Therefore, the distinct loading conditions play a dominant role, when performance and failure properties of asphalt mixtures are investigated in laboratory. In this context, fatigue testing of asphalt mixtures is widespread.

Fatigue is a key failure mode of poorly designed asphalt mixtures, when stress changes arising from repeated traffic loading under the atmospheric conditions weaken the coherence of the material in the long term. Even though the single stress arising from individual traffic loads is always lower than the material's ultimate strength, due to the gradual increase in the load repetitions, micro cracks initiate and accumulate, coalescing into macro cracks that finally lead to fatigue failure (Dowling, 1999).

Fatigue properties of asphalt mixtures under repeated loading is studied in laboratory using different homogeneous or non-homogeneous cyclic tests in different loading modes: uniaxial or triaxial, direct or indirect, bending, tension, compression or alternating tension and compression, and stress-controlled or strain-controlled (cp. European Standard EN 12697-24, 2012).

In conventional fatigue tests, pre-fabricated asphalt specimens are subjected to numerous continuous sinusoidal loading cycles at a single frequency and temperature, where the stress amplitude (or strain amplitude respectively in a strain-controlled test) is maintained over the whole test duration. Fatigue testing of one asphalt mixture relies on three different load amplitudes with at least three test replicates. For example, 18 asphalt specimens are tested according to European Standard (EN 12697-24, 2012). From all test replicates, a unique fatigue curve in form of a potential function is drawn, which represents fatigue life in function of applied stress amplitude (or strain amplitude respectively in a strain-controlled test). This specific fatigue function is used as key performance property for the durability of the asphalt mixture investigated. In some European countries, it also represents an important input to mechanistic pavement design, which aims to an optimization of the pavement layer thicknesses (see Mollenhauer and Wistuba, 2009).

Depending on the applied fatigue test type and procedure, fatigue properties of specific asphalt mixture are conventionally determined at a single test temperature in a range of 10-30°C (cp. EN 13108-20, 2016) in order to limit laboratory effort. However, as asphalt fatigue behaviour is driven by the rheological properties of the bitumen to a non-negligible extent, numerous authors claim that asphalt fatigue properties are highly dependent on test temperature (see e.g. Bodin et al., 2010; Ghuzlan and Carpenter, 2003; Mollenhauer and Wistuba, 2009; NCHRP, 2004). Fatigue tests which are limited to a single temperature, although in best accordance with European Standards, may provoke misleading conclusions.

B.2 Research background and approach

B.2.1 Fatigue evaluation of reclaimed and aged asphalt pavements

In last decades, increased demand for re-use of asphalt mixtures from reclaimed asphalt pavements (RAP) has led to increased recycling rates, which in some European countries exceed the value of 50 % (Hugener, 2017). RAP-containing asphalt mixtures are partly composed of fresh components, i.e. aggregate and bitumen, and of old components formed by the reclaimed aggregate which is coated with old bitumen. The bitumen properties have changed significantly due to ageing during pavement construction and time in service. Bitumen ageing is mainly attributed to the temperature dependent volatile loss of substance, making the bitumen highly elastic and brittle (see e.g. Airey, 2003). In general, RAP-containing asphalt mixtures are potentially more susceptible to cracking compared to fresh asphalt mixtures, especially in the low temperature range.

However, as postulated in the technical specifications, RAP-containing asphalt mixtures need to undergo the same conventional fatigue testing procedure as determined in the technical standards. As mentioned above, such fatigue tests are mostly limited to a single test temperature, and therefore may identify better fatigue resistance compared to the original asphalt mixtures with fresh aggregate, which is unexpected for low temperatures (cp. Mangiafico et al., 2017; Pérez-Martinez et al., 2016; Sonmez et al., 2016; Wistuba et al., 2015).

Similar conclusions were drawn for laboratory aged asphalt mixtures (Perez-Martinez et al., 2016; Van Den Bergh, 2001). Figure B.1 exemplary shows such observation, where results from classic fatigue tests are compared of fresh and laboratory aged AC 22 base course asphalt mixtures. Aging of the asphalt mixture was achieved by exposing the loose bitumen-covered aggregate to a temperature of 80 °C for a duration of 96 h, prior to compacting the mixture to form test specimens (aging procedure acc. to Büchler et al., 2009). Fatigue properties were determined in cyclic indirect tensile tests at a constant test temperature of 20 °C, and at a constant test temperature of 0 °C. Interestingly, considering the fatigue properties at the test temperature of 0 °C, the fresh asphalt mixture shows favorable fatigue properties compared to the aged mixture (Figure B.1). This indicates the importance of considering more than one test temperature for fatigue evaluation, regardless of the asphalt mixture considered. Consequently, a more reliable fatigue evaluation will lead to better correlation with in-field fatigue performance.

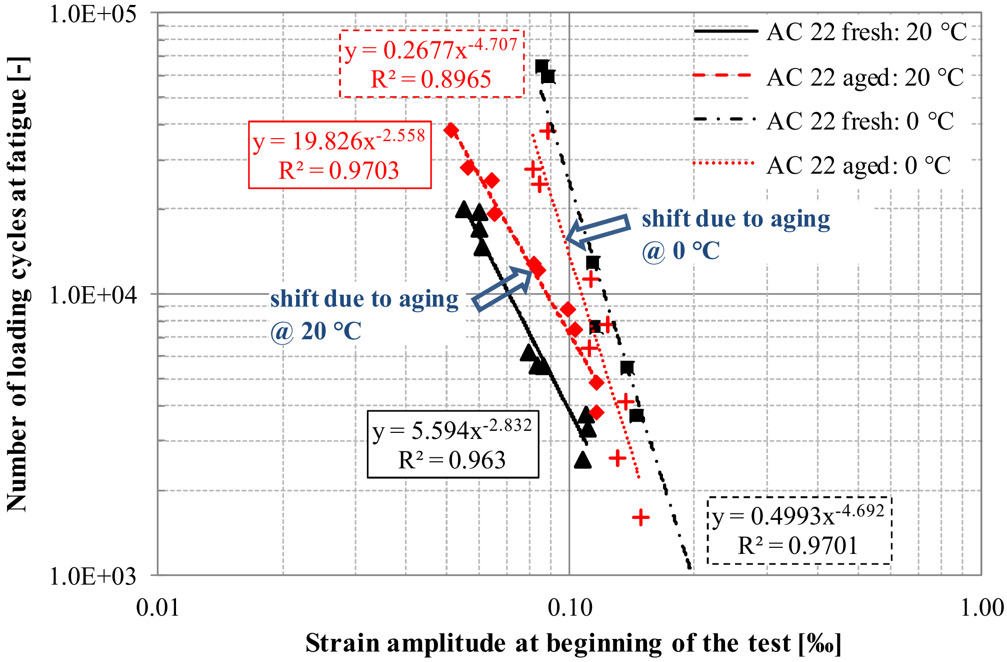


Figure B.1. Fatigue functions of fresh and aged base course asphalt mixture AC 22 in indirect tensile test at 20 °C and at 0 °C.

B.2.2 Research approach

In order to overcome the shortcomings when evaluating asphalt mixture fatigue properties in accordance with the European Standards, an alternative fatigue test protocol is presented in this study, which allows for plausible evaluation of asphalt mixture fatigue properties, while at the same time the test effort is limited to a minimum.

Based on numerous research efforts, it has been shown that accelerated fatigue tests in form of amplitude sweep can be successfully used for full fatigue evaluation of both binder and asphalt mixture, since this type of test appears to have the ability to indicate fatigue life as obtained by the conventional fatigue test (Hintz and Bahia, 2013; Johnson, 2010; Pérez-Jiménez et al., 2013). Therefore, the new fatigue protocol is based on frequency-amplitude sweep tests and on uniaxial tension-compression testing of prismatic asphalt mix specimens in stress-controlled mode. Fresh and aged asphalt mixtures for wearing course type AC 11 were considered.

Conventional fatigue tests and frequency-amplitude sweep tests were performed at different test temperatures. At low temperatures, the thermal induced cryogenic stress, as observed in thermal stress restrained specimen test (TSRST), was considered. Figure B.2 provides the flow chart of the research approach.

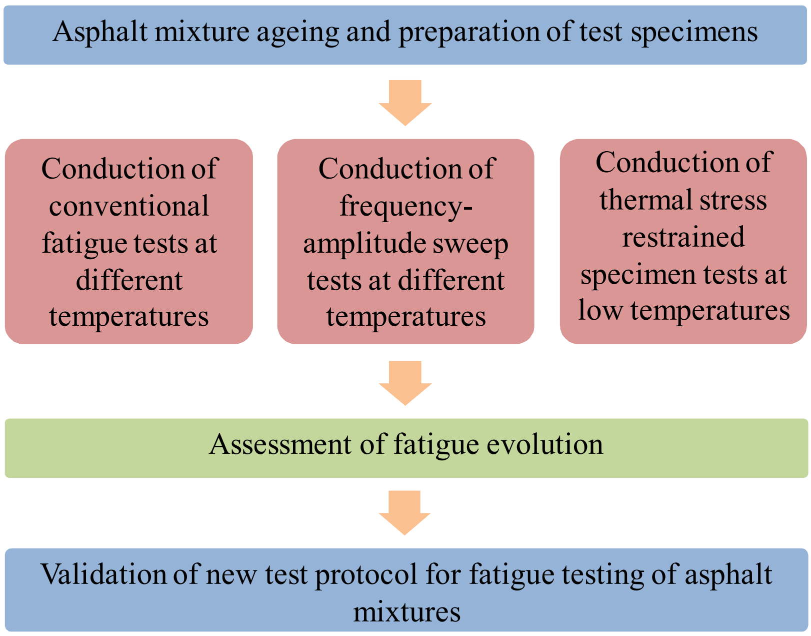


Figure B.2. Flow chart of the research approach.

B.3 Experimental study

B.3.1 Material composition and specimen preparation

Investigation of the fatigue properties was carried out using a standard asphalt mixture for surface courses, i.e. AC 11 (asphalt concrete, continuous grading, 11 mm maximum aggregate grain size) in fresh and aged conditions. The mixture gradation and composition characteristics are given in Table B.1.

Table B.1: Gradation and composition characteristics of AC 11 in fresh and aged condition

Gradation AC 11: Passing on sieve [M.-%]		**Composition characteristics:**	**Fresh AC 11**	**Aged AC 11**
0.063 mm	5	Binder type	50/70	
1 mm	23.2	Binder content [%]	5.7	
2 mm	36	Ring & Ball [°C]	60.4	71.4
5.6 mm	62.2	Volumetric mass density [g/cm^3]	2.640	
8 mm	74.2	Bulk density [g/cm^3]	2.493	2.480
11.2 mm	99.1	Air voids content [%]	5.57	6.06

For aging simulation in laboratory, the loose non-compacted mixture was spread on a grid and exposed to hot air (80 °C) for 96 h (4 days) in order to achieve homogenous ageing of the asphalt mix components (Büchler et al., 2009). This was done to achieve an increase of more than 10 °C in softening point Ring and Ball compared to the original virgin binder (cp. Table B.1).

Asphalt mixture slabs having dimensions 320 × 200 × 50 mm^3 were prepared using the segmented steel roller compaction method (Wistuba, 2016). In order to monitor the temperature variation inside the asphalt specimen during cyclic loading, temperature sensors PT100 were placed in the loose mixture within the compaction mould prior to mix compaction (Figure B.3). Due to its relatively small size and robustness through ceramic housing, a good integration of the sensor in the asphalt mixture was achieved, without weakening the asphalt specimen internal structure. From the asphalt mixture slabs, prismatic specimens were cut with final dimensions of 50 × 50 × 160 mm^3 (final position of the temperature sensor is in the middle part of the specimen, Figure B.3).

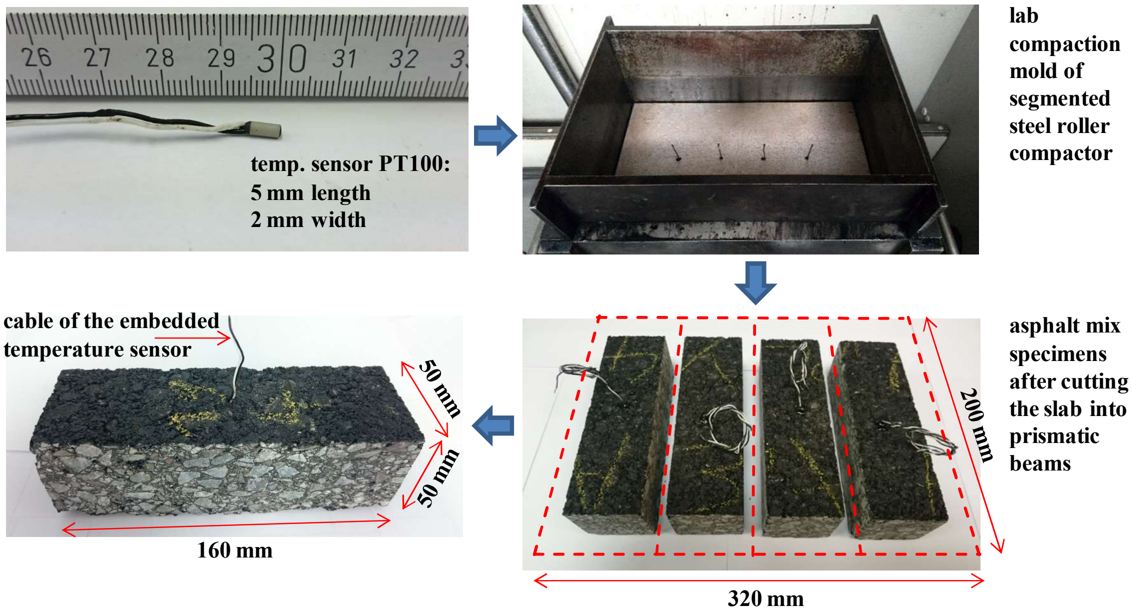


Figure B.3. Procedure for placing the temperature sensor PT100 for temperature monitoring inside the asphalt specimen.

B.3.2 Laboratory testing

Conventional fatigue tests and frequency-amplitude sweep tests on both fresh and aged asphalt mixtures were performed at following temperatures:

- 20 and 0 °C for conventional fatigue tests, and
- 20, 10, 0 and -10 °C for frequency-amplitude sweep tests.

Related to field observations, pavement structure is exposed to thermal cryogenic stress arising from the temperature decrease over time and restrained thermal contraction Wistuba et al., 2009). This thermally induced tensile cryogenic (low temperature) stress is highly asphalt mixture dependent and is to be considered for fatigue evaluation at low temperatures, since traffic-related stress may be superposed by tensile thermal stress (Arand, 1985; Mollenhauer and Wistuba, 2009; Pérez-Jiménez et al., 2011). For this reason, the thermal stress restrained specimen tests were additionally performed in order to determine cryogenic stresses at 10 °C, 0 °C and -10 °C for both fresh and aged asphalt mixtures.

B.3.2.1 Thermal stress restrained specimen test

TSRST is designed to simulate the weather-induced cooling of an asphalt pavement and intends to recover the thermal cryogenic stress arising from suppressed material shrinking. During TSRST, the specimen is held at constant length, while its temperature is decreased from a start temperature of 20 °C with a constant cooling rate of ΔT = -10 °C/h. A close-loop control system keeps the specimen at constant length. Due to the prohibited thermal shrinkage, the specimen is objected to an increasing cryogenic tensile stress. The test ends at a minimum test temperature of -40 °C or at failure respectively, when the cryogenic stress reaches the tensile strength of the asphalt specimen. TSRST results in a temperature-dependent function of cryogenic stress (σ_{cry}).

B.3.2.2 Conventional fatigue test

Evolution of the fatigue properties was performed using uniaxial tension-compression test in stress-controlled mode. This type of test is common for fatigue evaluation, since it simulates both tensile and compressive stresses occurring in the pavement due to wheel loading (Wistuba and Perret, 2004). Figure B.4 shows the test setup used. The most important parameters for material analysis, such as stress amplitude, strain amplitude, temperature, etc., were monitored and recorded during the entire test duration.

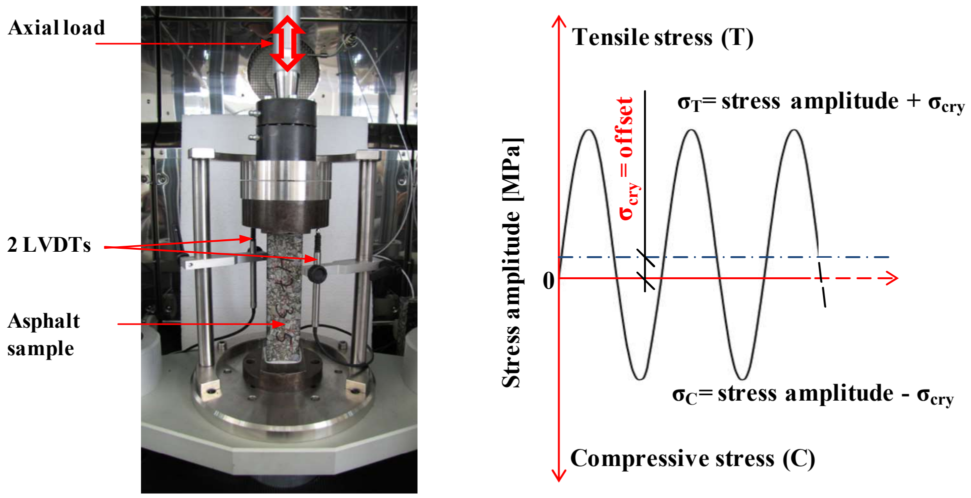


Figure B.4. Test setup for uniaxial tension compression fatigue test (left) and principle of applying thermal cryogenic stress (σ_{cry}) (right).

Conventional continuous fatigue tests (cp. EN 12697-24, 2012) were performed at two temperatures (20 °C and 0 °C) and at a fixed frequency of 10 Hz. An additional cryogenic tensile stress (σ_{cry}), as observed in TSRST, was applied as an offset in the stress signal (see Figure B.4, right). In order to optimize the test duration, the following stress amplitudes were applied for testing both fresh and aged asphalt mixtures:

- 0.7 MPa, 0.9 MPa and 1.2 MPa, at 20 °C always, and
- 1.8 MPa, 2.0 MPa and 2.25 MPa, at 0 °C always.

For the determination of the number of loading cycles until fatigue, the approach based on the energy ratio (*ER,* Equation B.1) proposed by Rowe and Bouldin (2000) was used. By plotting *ER* versus the number of loading cycles, the fatigue life is defined as the number of loading cycles when *ER* is maximum. This number of loading cycles represents the transition between micro cracking and macro cracking and is specified as N_{Macro}.

$$ER_n = n \cdot |E| \quad \text{[MPa]}, \tag{B.1}$$

where: ER_n = energy ratio at cycle n [MPa], n = cycle number [-], $|E|$ = absolute value of complex modulus at cycle n [MPa].

In order to obtain the fatigue functions for all test temperatures and mixture variants (fresh and aged), three stress amplitudes were considered with at least three test repetitions (resulting in 9 asphalt samples in total).

B.3.2.3 Frequency-amplitude sweep test protocol

The frequency-amplitude sweep test was performed using uniaxial tension-compression test apparatus in strain control and stress control (cp. Figure B.4, left) at four test temperatures (20, 10, 0 and -10 °C).

The new fatigue test procedure relies on frequency sweep and on amplitude sweep. The frequency sweep is intended for determination of the asphalt mixture viscoelastic properties, and the amplitude sweep is intended for evaluation of the asphalt mixture fatigue properties. A scheme is represented in Figure B.5, and explained in the following.

The test starts with a strain-controlled frequency sweep, considering six different frequencies in a range from 0.1 to 10 Hz. Due to the relatively low strain amplitude of 50 µm/m, the total number of 300 cycles in frequency sweep does not generate any fatigue damage in the asphalt specimen, as known from laboratory experience and as specified in the European Standards. The number of loading cycles for each frequency was limited to an appropriate number to effectively determine the complex modulus value. Depending on the test machine used, this number of loading cycles for each frequency deviates, but should always be kept as low as possible.

Thereafter an amplitude sweep at the fixed frequency of 10 Hz is applied on the same specimen. The stress amplitude starts from 0.35 MPa (associated to an elastic strain of 50 µm/m at 20 °C at the beginning of the test) and is increased stepwise in increments of 0.15 MPa until the specimen fails. Each loading sequence consists of 2000 loading cycles. This number of loading cycles was chosen through a pre-testing procedure in such a way that the laboratory effort remains acceptable.

At each test temperature, at least 3 test repetitions are run (resulting in 12 asphalt samples in total), and the corresponding number of total loading cycles at failure are determined.

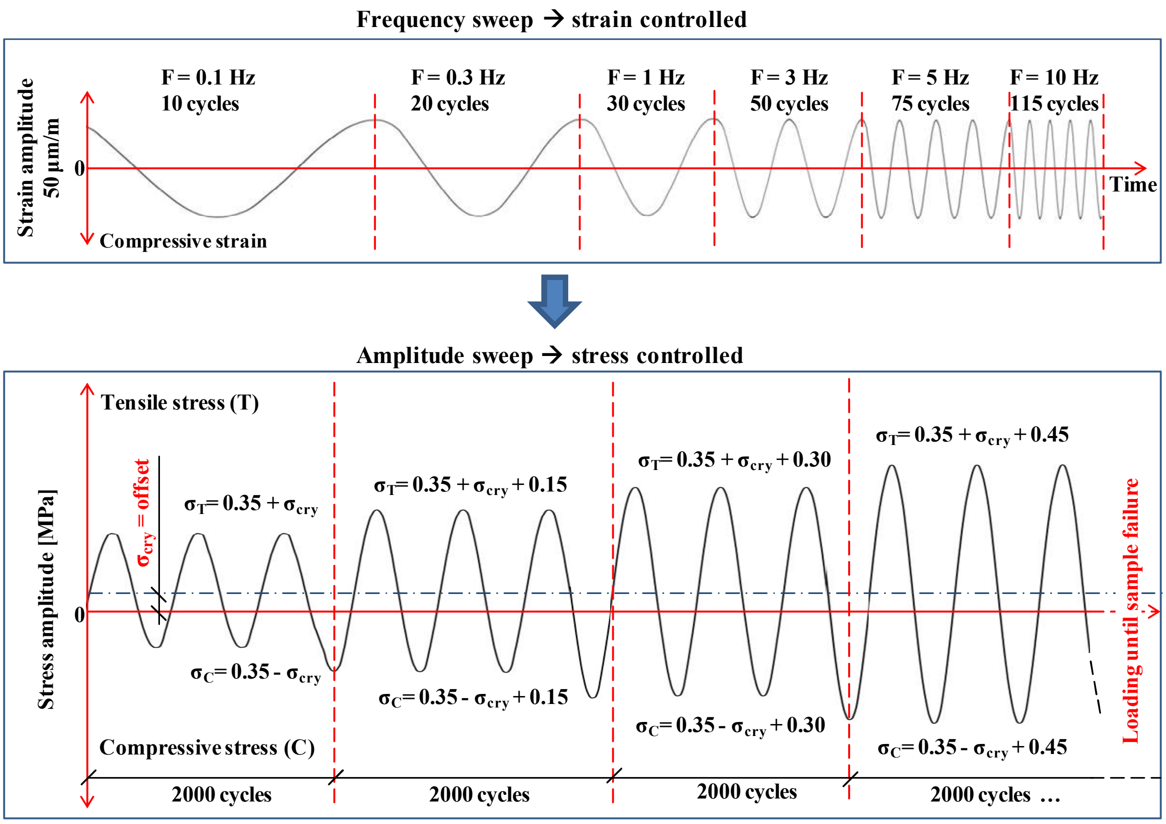


Figure B.5. Schematic procedure of the new frequency-amplitude sweep test protocol for fatigue testing of asphalt mixtures.

B.4 Test results

B.4.1 Thermal stress restrained specimen tests

Cryogenic stresses derived for both fresh and aged asphalt mixtures, with three test repetitions are shown in Figure B.6, where cryogenic tensile stresses are plotted over temperature. The fresh asphalt mixture accumulates slightly less cryogenic tensile stress, and therefore should advantageously influence fatigue resistance.

Cryogenic stresses to be considered for fatigue testing are presented in Table B.2.

Table B.2: Cryogenic stresses for fresh and aged asphalt mixtures at 10, 0 and -10 °C

	Fresh AC 11	Aged AC 11
Cryogenic stress at 10 °C [MPa]	0.031	0.040
Cryogenic stress at 0 °C [MPa]	0.191	0.284
Cryogenic stress at -10 °C [MPa]	0.865	1.044

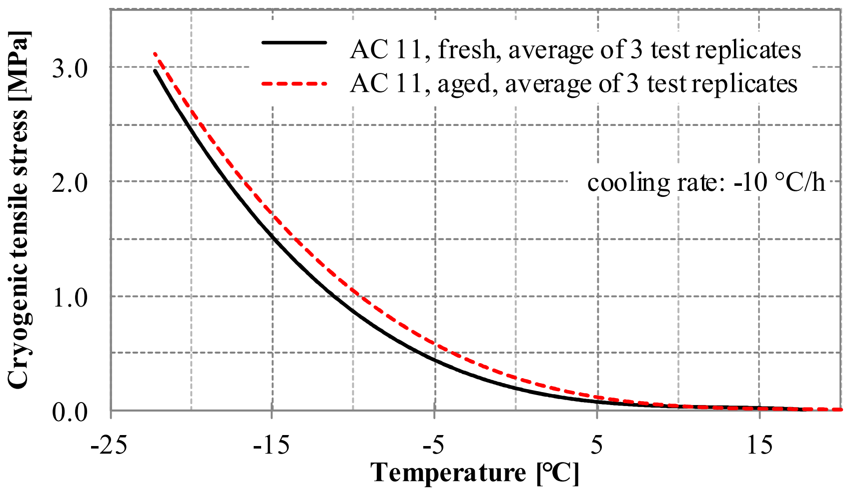


Figure B.6. Cryogenic tensile stresses over temperature, stated in TSRST for fresh and aged asphalt mixtures.

B.4.2 Conventional fatigue test

During fatigue testing, as a consequence of the increased excitation due to cyclic loading, the absolute value of complex modulus is reduced continuously during the test. An example is demonstrated in Figure B.7, where complex modulus, energy ratio and specimen core temperature are plotted over the number of loading cycles for fresh asphalt mixture tested at 20 °C. Due to the viscous energy dissipation, an increase of the specimen core temperature of 1.41 °C (until macro cracking) is recorded by the embedded temperature sensor.

Figure B.8 shows the obtained fatigue functions, in terms of potential functions in log-log scales for fresh and aged asphalt mixtures at 20 °C and 0 °C. Even though the cryogenic tensile stress was considered at 0 °C, the specimens of both asphalt mixtures show increased fatigue resistance with decreased test temperature. At 20 °C the specimens of the aged asphalt mixture show better fatigue resistance compared to the one of fresh asphalt mixture, which is due to the increased material stiffness of the aged asphalt mixture. At 0 °C the contrary is observed, showing a shift for the aged asphalt specimen to inferior fatigue resistance.

The temperature increase during cyclic excitation measured until macro crack initiation (N_{Macro}) does not significantly change in terms of material type (fresh or aged asphalt mixture), but it is highly dependent on test temperature. At 20 °C some asphalt mixture specimens showed a temperature change of 2.2 °C. Such temperature increase can significantly influence the fatigue and recovery properties of the asphalt mixture (cp. Di Benedetto et al., 2011; Isailović et al., 2017). Fatigue testing at 0 °C does not induce such temperature development, where the average increase is 0.52 °C.

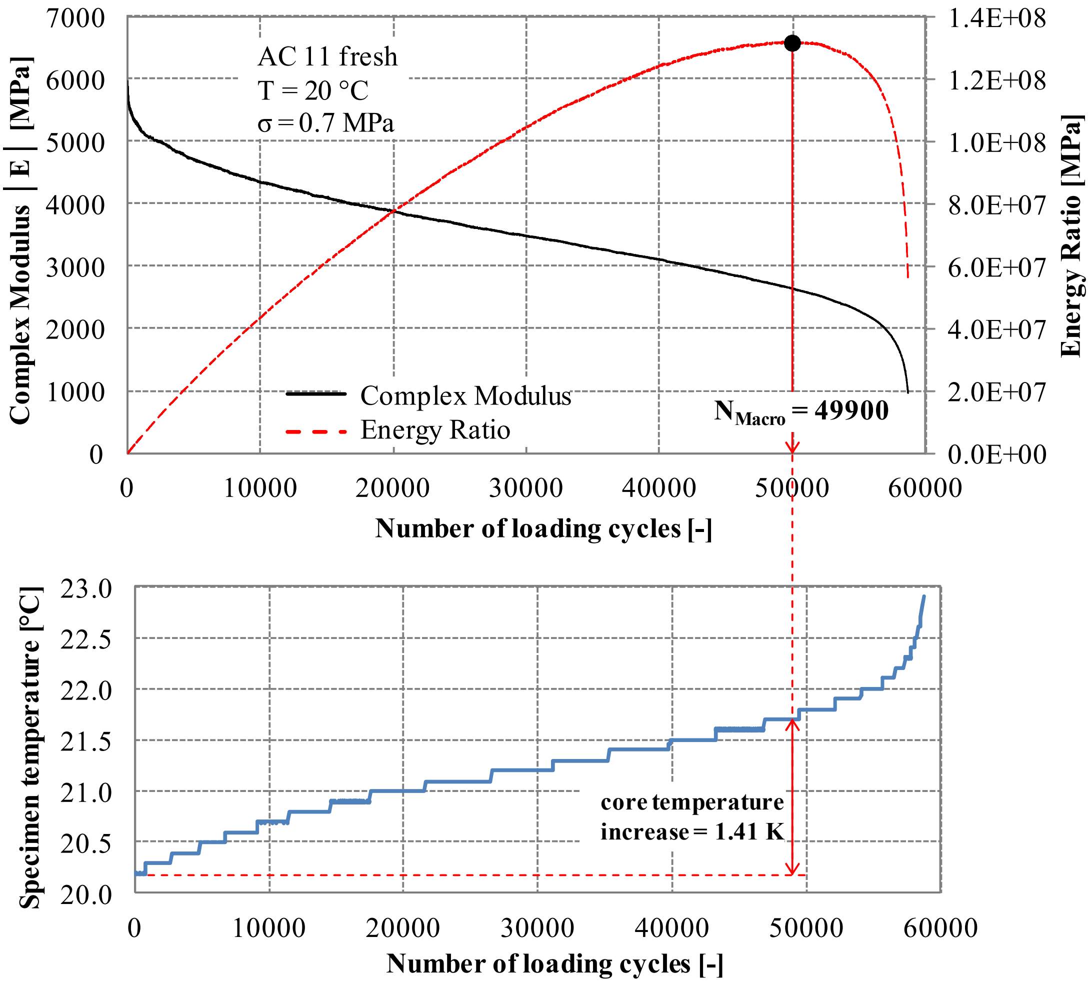


Figure B.7. Evolutions of absolute value of complex modulus, energy ratio, and specimen core temperature in function of number of loading cycles in (conventional) tension-compression fatigue test at 20 °C and for 0.7 MPa stress amplitude for fresh asphalt mixture AC 11.

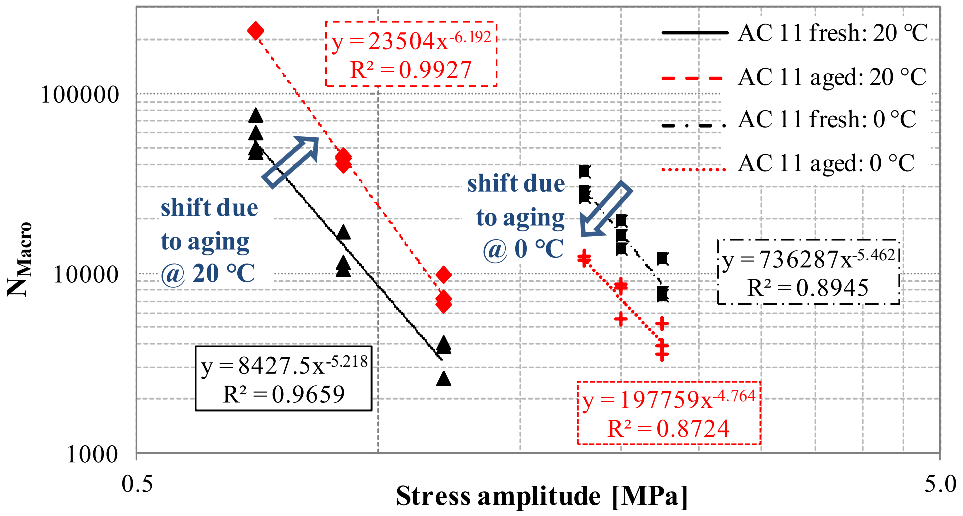


Figure B.8. Fatigue functions for fresh and aged asphalt mixtures AC 11 in conventional tension-compression fatigue tests at 20 °C and 0 °C.

B.4.3 Frequency-amplitude sweep tests

B.4.3.1 Frequency sweep

Figure B.9 exemplarily shows the average complex modulus values obtained from 12 tested asphalt specimens in frequency-amplitude sweep tests at 4 temperatures and 6 frequencies for fresh asphalt mixture. Each point in the diagram represents the mean value of three test repetitions.

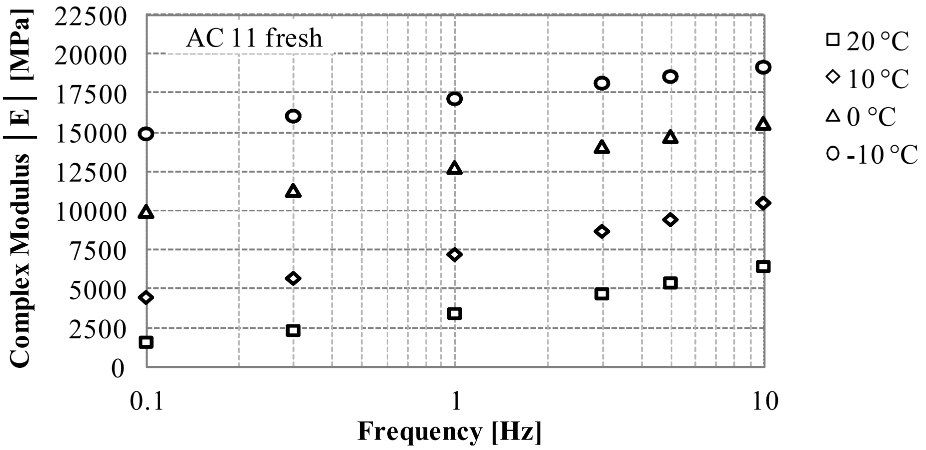


Figure B.9. Complex modulus values in dependence of temperature and frequency obtained from frequency sweep test for fresh asphalt mixture.

Based on the principle of time-temperature correspondence (Pellinen, 1998), the master curve can be drawn using a reference temperature (T_{Ref}) of 10 °C. The temperature shift of the complex modulus is obtained using the Arrhenius equation, reading

$$\log \alpha_T = \frac{0.4347 \cdot E_a}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \qquad [-], \qquad (B.2)$$

where: α_T = shift factor [-], R = ideal gas constant [8.314 J/mol.K], T = experimental temperature [°C], T_{Ref} = reference temperature [°C].

The master curve is modeled using a sigmoidal function, reading

$$|E| = y_0 + \frac{w}{1 + e^{-\left(\frac{x - x_0}{z}\right)}} \qquad [\text{MPa}], \qquad (B.3)$$

where: $|E|$ = absolute value of complex modulus [MPa], y_0, w, x_0, z = model parameters [-], x = logarithms of reduced frequency $\log(\alpha_T \cdot f)$.

The model parameters are obtained by minimizing the sum of square of errors between experimental and modeled values using the solver function in an Excel spreadsheet.

Figure B.10 represents the resulting master curves for fresh and aged asphalt mixtures for the reference temperature of 10 °C. Due to the increased binder stiffness, the aged asphalt mixture shows higher complex modulus values in the high temperature range. Interestingly, if considering temperatures below 7 °C the fresh asphalt mixture is stiffer than the aged one. This is probably due to the slightly decreased bulk densities of aged asphalt samples (cp. Table B.1), where increased binder stiffness cannot compensate the relatively internal structure.

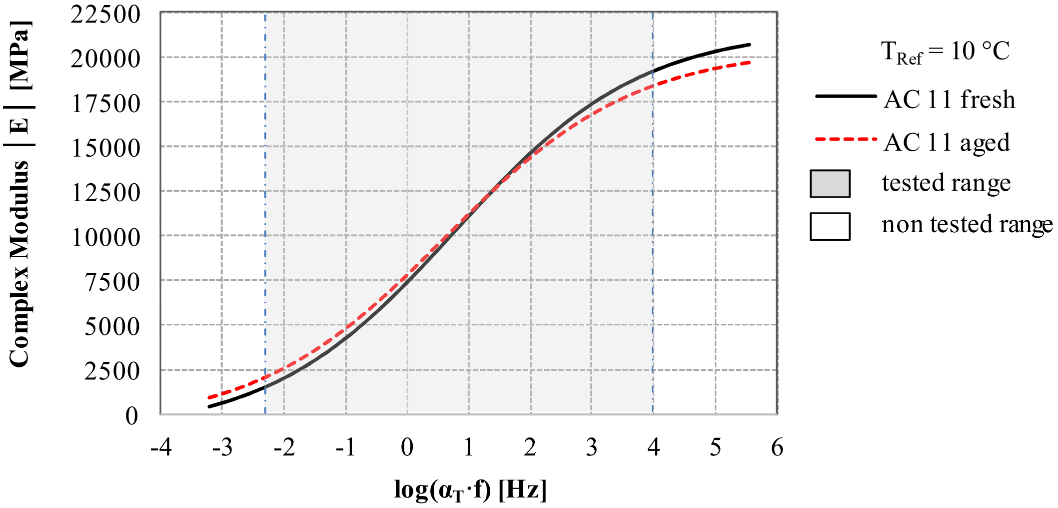


Figure B.10. Master curves for fresh and aged asphalt mixtures for a reference temperature of 10 °C.

It should be noted, that the tested temperature range from 20 °C to -10 °C can be extended with minor laboratory effort in order to better estimate the complex modulus values at respectively high and low temperatures.

B.4.3.2 Amplitude sweep

Subsequent to the strain-controlled frequency sweep, amplitude sweep in stress-controlled mode was performed until asphalt specimen failure. As a consequence of the increased stress amplitude and the cyclic excitation, the absolute value of complex modulus is continuously reduced (see example in Figure B.11). Contrary to conventional fatigue testing (cp. Section B.4.2), the evolution of the absolute value of complex modulus does not show three disparate phases. The first phase (rapid decrease of the complex modulus) does not exist, because the effects of nonlinearity, thixotropy and heating are relatively small at low stress amplitudes. Due to viscous energy dissipation, an increase of the specimen core temperature is recorded by the embedded temperature sensor (Figure B.11).

For each test temperature, at least three test repetitions were run. The resulting average fatigue lives (N_{Macro}) of 12 fresh and 12 aged asphalt samples, fitted with polynomial functions, are shown in Figure B.12. The scatter of results was determined for a coefficient of variation of less than 0.1.

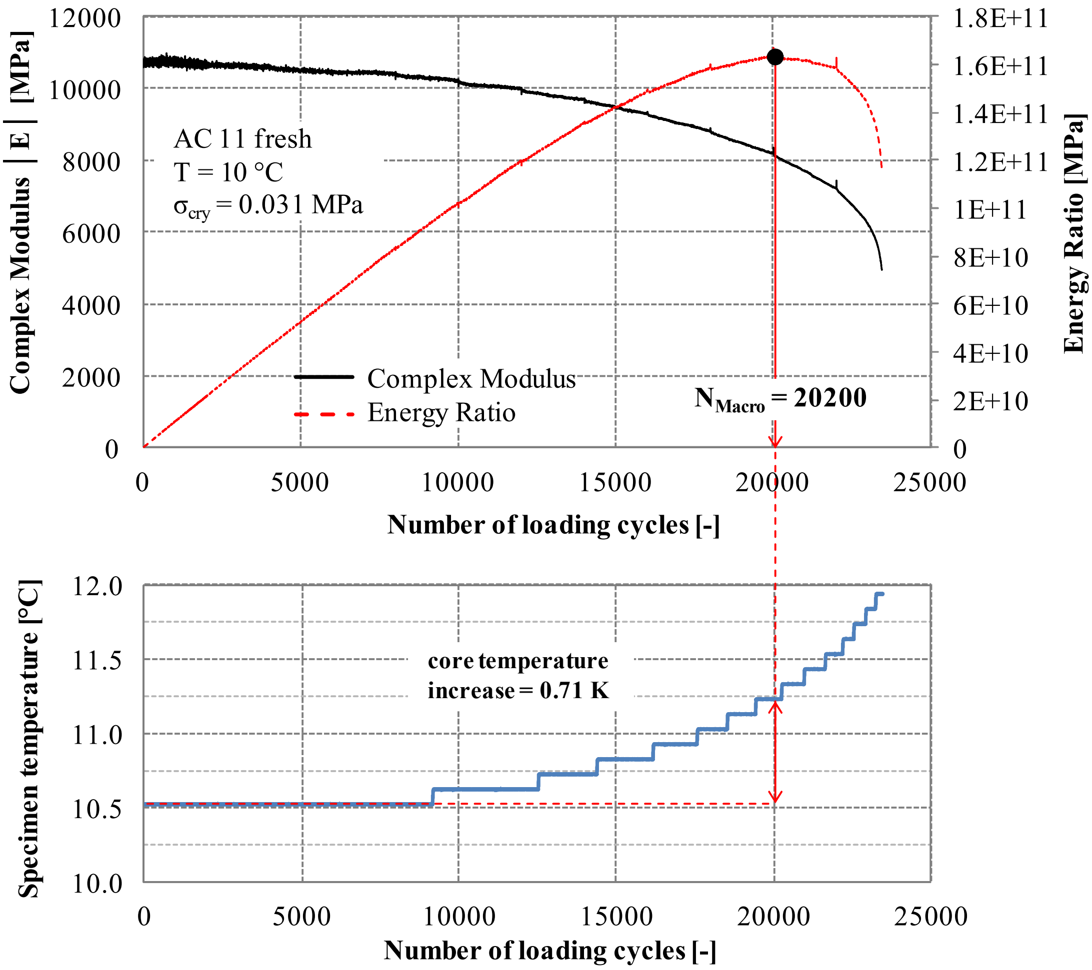


Figure B.11. Evolution of the absolute value of complex modulus, energy ratio and specimen core temperature in function of the number of loading cycles in the amplitude sweep for fresh asphalt mixture at 10 °C.

Similarly to the results from conventional fatigue tests, a decrease in test temperature to 0 °C leads to better fatigue resistance. Below 0 °C, the fatigue properties of fresh asphalt mixture continued to increase. Contrary, the N_{Macro} values of aged asphalt mixture reached their maximum at approximately -3 °C, where an additional drop of the test temperature leads to fatigue resistance reduction.

By comparing the average N_{Macro} values at 20 °C and at 0 °C of fresh and aged asphalt mixtures (Figure B.12), the mixture ranking is identical as observed in the conventional fatigue tests (cp. Figure B.8). In addition, it is shown, that aging significantly reduces fatigue resistance at low temperatures. This is clearly illustrated in Figure B.12, by comparing the area underneath the polynomial functions, where the fresh asphalt mixture shows a considerable bigger area. It becomes obvious, that the punctual fatigue evaluation as in conventional fatigue testing (e.g. at 20 °C) leads to misleading fatigue evaluation putting advantage on the aged asphalt mixture.

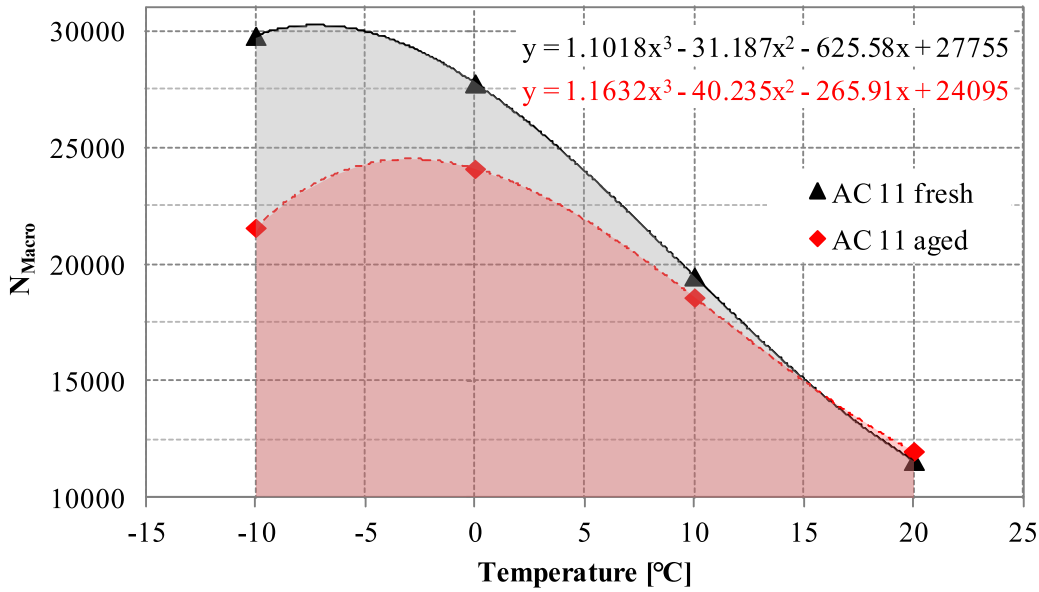


Figure B.12. Resulting average N_{Makro} values of 12 fresh and 12 aged asphalt samples (fitted with polynomial functions) in amplitude sweep at 4 test temperatures.

Similarly to the conventional fatigue results, the temperature increase during cyclic excitation measured until macro crack initiation (N_{Macro}) does not significantly change in terms of material aging. Again, higher temperatures contribute more to the specimens heating, where at 20 °C the temperature change was up to 0.80 °C. Due to the significantly lower specimen heating compared to conventional fatigue testing, the fatigue results will be less influenced. At 0 °C the average increase was 0.42 °C.

B.5 Summary and conclusions

In this study, the fatigue properties of fresh and aged asphalt mixtures were investigated, using cyclic uniaxial tension-compression test run in two different modes: conventional fatigue test and fatigue test based on sweep test at multiple amplitudes and frequencies.

The conventional fatigue evaluation in accordance with the European Standards at single temperature results in general in a better fatigue resistance for the aged asphalt mixture, compared to the original fresh mixture. This does not correlate with expectance, and therefore, the punctual fatigue evaluation at single test temperature is not reliable.

Since asphalt mixture fatigue properties are highly temperature dependent, it is concluded, that fatigue tests need to be run for a wide temperature range. Therefore, a new fatigue procedure is proposed, relying on frequency-amplitude sweep tests at 4 different temperatures between 20 °C and -10 °C. A frequency sweep (intended for evaluation of viscoelastic properties) is followed by an amplitude sweep (intended for evaluation of fatigue resistance) until specimen failure. Based on complex modulus values from frequency sweeps at four temperatures and six frequencies the asphalt mixture master curve can be drawn. Due to the temperature variation, a plausible evaluation of the asphalt mixture fatigue performance obtained from amplitude sweeps was observed, where the fresh asphalt mixture showed significantly improved fatigue resistance compared to the aged one.

The alternative test protocol with frequency-amplitude sweep tests requires a marginally increased laboratory effort if comparing to conventional fatigue testing (12 instead of 9 test samples), however, the plausible fatigue evaluation and determination of mixture viscoelastic properties are most beneficial.

Since these findings are based on investigations on a limited number of asphalt mixture types, extended research is needed in order to validate the proposed fatigue evaluation procedure.

B.6 References

Airey, G.D. 2003. State o the art report on aging test methods for bituminous pavements. International Journal of Pavement Engineering, Vol. 4, pp. 165-176.

Arand, W. 1985. Influence of bitumen hardness on the fatigue behavior of asphalt layers. Proc., 3rd Eurobitume-Symposium, Vol. 1, pp. 164 - 167, Sept. 11-13, 1985, Den Haag, The Netherlands.

Büchler, S., Mollenhauer, K.,Wistuba, M., and Renken, P. 2009. Aging of stone mastic asphalt and evaluation of cracking resistance. Proc., 8th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields, University of Illinois at Urbana-Champaign, June 29-July 2, 2009, Champaign, Illinois, USA.

Bodin, D., Terrier, J.P., Perroteau, C., and Hornych, P. 2010. Effect of temperature on fatigue performance of asphalt mixes. Proc., Int. Symposium on Asphalt Pavements ISAP, Aug. 1-6, 2010, Nagoya, Japan.

Di Benedetto, H., Nguyen, Q-T., and Sauzéat, C. 2011. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 12(1), pp. 129-158.

Dowling, N. E. 1999. Mechanical behavior of materials, engineering methods for deformation, fracture, and fatigue. Second Edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

EN 12697-24. 2012. Test methods for hot mix asphalt - Part 24: Resistance to fatigue. European Standard.

EN 13108-20. 2016. Bituminous mixtures - Material specifications - Part 20: Type testing. European Standard.

Ghuzlan K. and Carpenter, S. 2003. Traditional fatigue analysis of asphalt concrete mixtures. Transportation Research Board, Annual meeting (CD-ROM), Paper No. 61801.

Hintz, C., and Bahia, H. 2013. Simplification of linear amplitude sweep test and specification parameter. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2370, pp. 10-16.

Hugener, M. 2017. Hot recycling: state of the art and new challenges in Europe. International forum, Association of Asphalt Paving Technologists Conference (AAPT), Mar. 19-22, 2017, Newport Beach, California, USA.

Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Influence of rest period on asphalt recovery considering nonlinearity and self-heating. Journal of Construction and Building Materials, Vol. 140, pp. 321-327.

Johnson, C. M. 2010. Estimating asphalt binder fatigue resistance using an accelerated test method. Thesis, University of Wisconsin, Civil & Environmental Engineering, Madison, USA.

Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, F. and Planque, L. 2017. Complex modulus and fatigue performances of bituminous mixtures with reclaimed asphalt pavement and a recycling agent of vegetable origin. Journal of Road Materials and Pavement Design, Vol 18. No. 2, pp. 315-330.

Mollenhauer, K., and Wistuba, M. 2009. Fatigue testing of hot mix asphalt - Is there a way to reduce the test effort while getting adequate input for pavement design? Proc., 8th International conference on the bearing capacity of roads, railways, and airfields, June 29 - July 2, 2009, Champaign, Illinois, USA.

NCHRP. 2004. Guide for mechanistic-empirical design of new and rehabilitated pavement structures. Appendix II-1: Calibration of fatigue cracking models for flexible pavements. Illinois, USA.

Pellinen, T. 1998. The assessment of validity of using different shifting equations to construct a master curve of HMA; University of Maryland: College Park, MD, USA.

Pérez-Jiménez, F., Miró, R., and Martínez A.H. 2011. Effect of thermal stresses on fatigue behavior in bituminous mixes. Transportation Research Record, Journal of the Transportation Research Board, No. 2210, pp. 90-96.

Pérez Jiménez, F.E., Botella Nieto, R., Martínez Reguero, A.H., and Miró Recasens, J.R. 2013. Estimating the fatigue law of asphalt mixtures using a strain sweep test (EBADE test). Proc., 5th International EATA Conference, Jun. 3-5, 2013, Braunschweig, Germany.

Perez-Martinez, M., Marsac, P., Gabet, T., Hammoum, F., Mesquita Lopes, M. and Pouget, S. 2016. Effects of ageing on warm mix asphalts with high rates of reclaimed asphalt pavement. Proc., 8th International RILEM Conference on Mechanisms of Cracking and Debonding in Pavements, Vol. 13, Jun. 7-9, 2016, pp. 113-118, Nantes, France.

Rowe, G.M., and Bouldin, M. G. 2000. Improved techniques to evaluate the fatigue resistance of asphaltic mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, Sept. 20-22, 2000, Barcelona, Spain.

Sonmez, I., Ali Yildirim, S., and Temren, Z. 2016. Investigation of performance properties of laboratory and plant produced bituminous mixture containing high rates of reclaimed asphalt. Proc., 6th Eurasphalt & Eurobitume Congress, Jun. 1-3, 2016, Prague, Check Republic.

Van den Bergh. 2011. The effect of ageing on the fatigue and healing properties of bituminous mortars. Thesis. Delft University of technology, The Netherlands.

Wistuba, M., and Perret, J. 2004. Comparative strain measurement in bituminous layers with the use of ALT. Proc., 2nd international conference on accelerated pavement testing, Sept. 25-29, 2004, Minneapolis, Minnesota, USA.

Wistuba, M., Monismith, C., Bahia, H.U., Renken, P., Olard, F., Blab, R., Mollenhauer, K., Metzker, K., Büchler, S., Grönniger, J., Zeng, M., and Nam, K. 2009. Asphalt material behaviour at low temperatures. Essays in honour of Professor Wolfgang Arand on the occasion of his 80th birthday. Schriftenreihe Straßenwesen, Heft Nr. 23, Braunschweig Pavement Engineering Centre, Technische Universität Braunschweig.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

Wistuba, M. P., Grönniger, J., and Isailović, I. 2015. Optimierung des Recyclinganteils in Asphalttrag- und -binderschichten (ORAB). Forschungsprojekt F&E-Projekt ORAB i.A. Schlussbericht, Bundesministerium für Verkehr, Innovation und Technologie ÖBB-Infrastruktur AG Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft, Bundesministerium für Verkehr, Innovation und Technologie, Abteilung Mobilitäts- und Verkehrstechnologien, Wien, Austria.

C Investigation on mixture recovery properties in fatigue tests[3]

Abstract: In this paper the asphalt mixture recovery properties in fatigue tests are investigated based on dissipated energy approach. In order to determine the influence of material ageing, bitumen content, polymer modification and compaction energy on material ability to recover its initial characteristics, different variations of an asphalt mixture for surface course AC 11 D S were prepared. Recovery of material mechanical properties is observed during a single rest period, introduced into tension-compression cyclic fatigue tests under stress control. The analysis of the experimental results reveals that there is a significant influence of the duration of rest period on recovery capability. A plateau phase is achieved when the length of the rest period does not have any impact on asphalt recovery properties. Asphalt ageing plays an important role in reducing the effects of material recovery. The degree of compaction used in this research seems to have no influence on material ability to restore its initial properties. Mixtures prepared with additionally 0.5 % of bitumen by mass show the best recovery characteristics compared to other variations.

Keywords: dissipated energy; rest period; material recovery properties.

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[3] Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Investigation on mixture recovery properties in fatigue tests. Published in Journal of Road Materials and Pavement Design, pp. 1-11, DOI: 10.1080/14680629 .2017.1300598, Taylor and Francis.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 85 %

C.1 Introduction

Understanding the recovery properties of asphalt materials is fundamental for improving the mix design, the construction methods and the field response of asphalt pavements. Therefore, the rest period occurring between repeated axles loads of the same or of different vehicles represents one of the critical parameters which may significantly influence the long-term pavement performance.

Traditional laboratory test methods for characterizing the fatigue life of asphalt mixtures do not include rest periods in the testing procedure, since this would imply longer tests durations, which may not be practical on a routine basis; hence, their influence on pavement life is commonly neglected. Nevertheless, the current testing methods are not necessarily representative of the effective loading spectrum which a real pavement experiences.

When comparing the number of cycles required for achieving fatigue failure from conventional laboratory experiments with the actual field measurements, longer field fatigue life is observed. To take into account this difference, shift factors are conventionally adopted to match field observations and laboratory results (Carpenter and Shen, 2006). This is because rest periods allow a certain degree of recovery of material mechanical properties. This is associated with a number of phenomena such as relaxation of stresses (due to the material viscoelasticity) and healing of the micro cracks occurred in the asphalt mixture (Kim and Roque, 2006), resulting in an extended durability of the pavement. This has been recognized by many researchers and a considerable number of studies show significant impact of rest phases on the damage evolution in asphalt structures (Carpenter and Shen, 2006; Kim and Roque, 2006; Little et al., 1999; Shen et al., 2009).

The recovery capability of asphalt mixtures having different mix design is experimentally investigated in the present research by introducing rest periods of various durations in the tests procedure. The dissipated energy approach which is a fundamental analysis tool for observing the difference in material behaviour during cyclic loading is used for analyzing the material recovery properties (Carpenter and Shen, 2006). In particular, it is expected that the findings can be used for selecting better pavement materials, since the asphalt material that has higher recovery capability accumulates less deformation and less damage in the asphalt layer (Luo et al., 2013).

C.2 Experimental study

C.2.1 Material composition

Fatigue recovery tests were performed on a set of asphalt mixtures of a surface course mix type AC 11 D S. All asphalt mixtures were prepared with aggregate of a maximum grain size of 11 mm. Figure C.1 presents the aggregate gradation curve. Plain bitumen with penetration grade 50/70 and a polymer-modified bitumen 25-55/55 were used (5.9 % by total mix weight).

Test specimens were cut from slabs ($500 \times 700 \times 40$ mm^3) made using the segmented steel roller compaction method (see Figure C.2). Using the standard compaction procedure it is possible to produce asphalt mixture slabs with nearly the same characteristics (air voids distribution, particle distribution, particle orientation and performance properties) compared to those in the field (Renken, 2000). The compactor uses a steel roller cylindrical sector to produce a kneading action and downward force to the specimen in both pre-compaction and main compaction phases (see Wistuba, 2014). The pre-compaction phase is displacement controlled and is intended to simulate the compaction effort of the road paver. The main compaction phase is assumed to simulate the compaction by the road roller and consists of 12 roller passes in stress control.

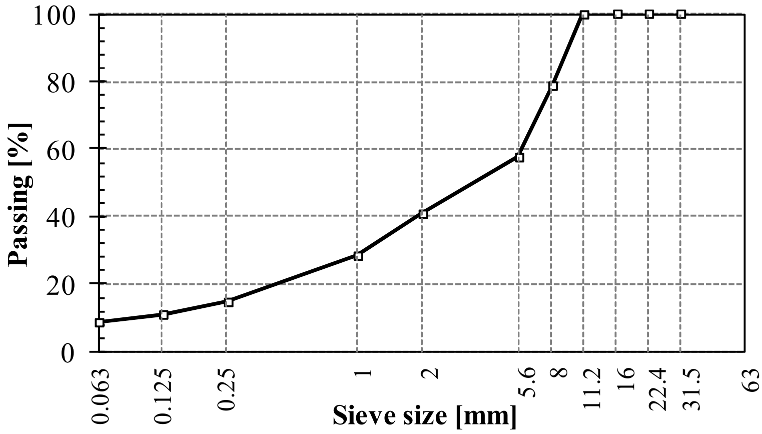

Figure C.1. Aggregate gradation curve used to prepare asphalt mixture specimens.

In addition, the following factors were modified for the preparation of specimen and in the basic mix design, which includes a plain bitumen 50/70:

- mixture long-term ageing using the Braunschweig Aging Protocol (Buchler et al., 2009) (final air voids content of 3.4 % in the compacted mixture),
- mixture preparation with additional 0.5 % bitumen by weight (final air voids content of 1.0 % in the compacted mixture),
- high slab compaction energy/effort of asphalt mixture introducing 14 rolling passes in the main compaction phase (final air voids content of 2.2 % in the compacted mixture),
- low slab compaction energy/effort of asphalt mixture introducing 10 rolling passes in the main compaction phase (final air voids content of 2.6 % in the compacted mixture).

Figure C.2. Segmented steel roller compactor at TU Braunschweig.

Long-term mixture ageing was simulated in the laboratory using the modified Strategic Highway Research Program ageing procedure (Bell, 1989). The loose non-compacted mixture was spread on a grid and exposed to hot air (80 °C) for four days in order to achieve the homogenous ageing of the asphalt mix components (Büchler et al., 2009). This was done to achieve an increase of 12 °C in softening point Ring & Ball compared to the original virgin binder.

C.2.2 Testing composition and test description

For the evaluation of the mixture recovery properties, the uniaxial stress-controlled tension-compression fatigue test was used. This test creates homogenous stress and strain fields in the middle portion of specimen and represents a reasonable configuration for the estimation of the fatigue life of asphalt mixtures (Di Benedetto, 2013). Figure C.3 presents the test equipment used in the present study.

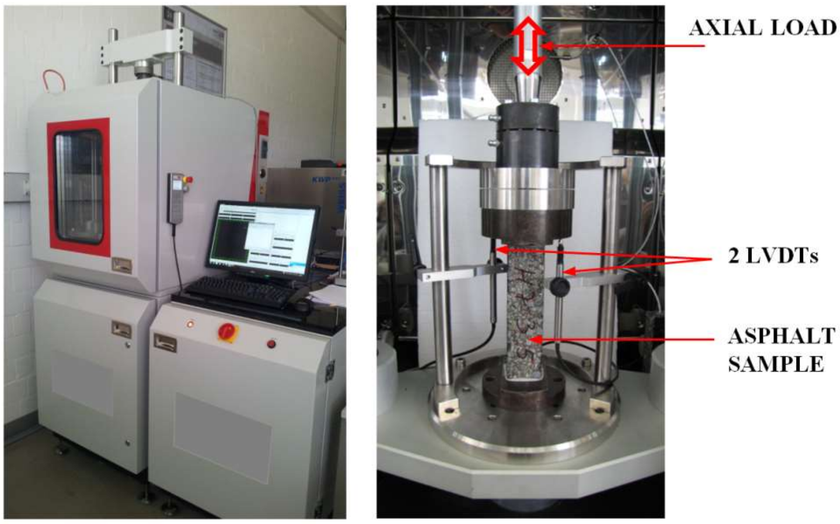

Figure C.3. Testing set-up used for the recovery evaluation.

A sinusoidal cyclic load in tension and compression at the effective stress amplitude of 1.05 MPa (associated elastic strain of 200 µm/m at the beginning of the test) was imposed on the prismatic specimens (specimen size 40 × 40 × 160 mm^3) in order to optimize test duration. A constant frequency of 10 Hz and a temperature of 20 °C were used during testing, with at least two test replicates. Loading was applied until the material experienced a decrease in the complex modulus down to 75 % of its initial value ($|E_{100}|$), determined at the 100th loading cycle (Phase 1, Figure C.4). Then, a single rest period (RP) was applied in order to allow the specimen to recover (partly or completely) its initial mechanical characteristics; during the rest period the specimen is stress-free. At the end of the rest period, the specimen is loaded with a new loading sequence (Phase 2, Figure C.4) till failure. Figure C.5 shows the applied rest period durations for specific mixture compositions.

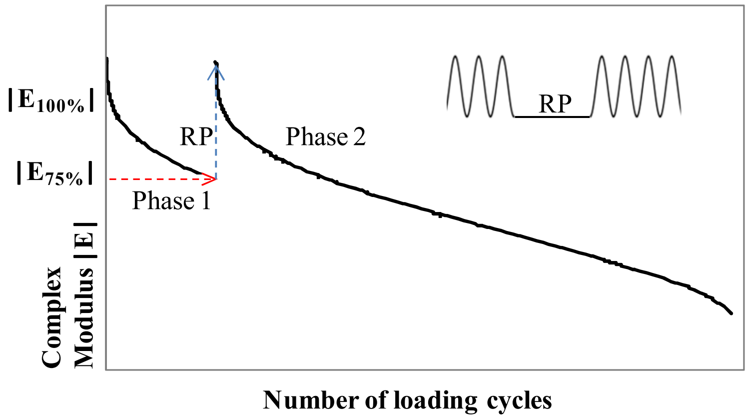

Figure C.4. Test protocol used to characterize asphalt mixture recovery capacity: Phase 1 + rest period (RP) + Phase 2.

The used testing procedure with one rest period does not simulate real loading conditions in the field, however, it provides the opportunity to better estimate the influence of the rest period on material recovery potential compared to procedures with rest periods after each loading cycle.

C.2.3 Recovery evaluation

Dissipated energy approach was used to investigate the asphalt mixture recovery properties. The energy dissipated within one loading cycle represents the difference between the energy provided to the material during the loading phase and the energy returned during unloading. Namely, if a material is perfectly elastic, the loading and unloading curves follow the same paths, meaning that all the energy is recovered or returned, without any energy dissipation (Figure C.6, left). In case of viscoelastic material, such as asphalt, loading and unloading curves do not overlap, which indicates loss of energy within the material. Part of the energy is dissipated out of the system through external work, heat generation or damage (Ghuzlan and Carpenter, 2000). The generated ellipse is called hysteresis loop and its area corresponds to the energy dissipated in one loading-unloading cycle (Figure C.6, right).

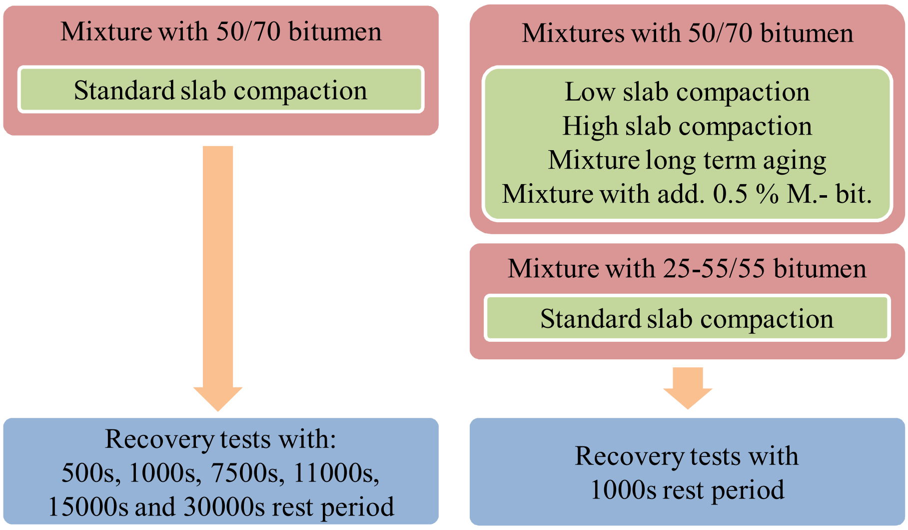

Figure C.5. Rest period durations for specific mixture compositions.

For the calculation of dissipated energy (W_n) in one loading cycle, the following equation can be used for linear viscoelastic materials:

$$W_n = \pi \cdot \sigma_n \cdot \varepsilon_n \cdot sin\varphi_n \quad [\mathrm{kJ/m^3}], \tag{C.1}$$

where: σ_n = the stress amplitude at cycle n [MPa], ε_n = the strain amplitude at cycle n [‰], φ_n = the phase angle at cycle n [°].

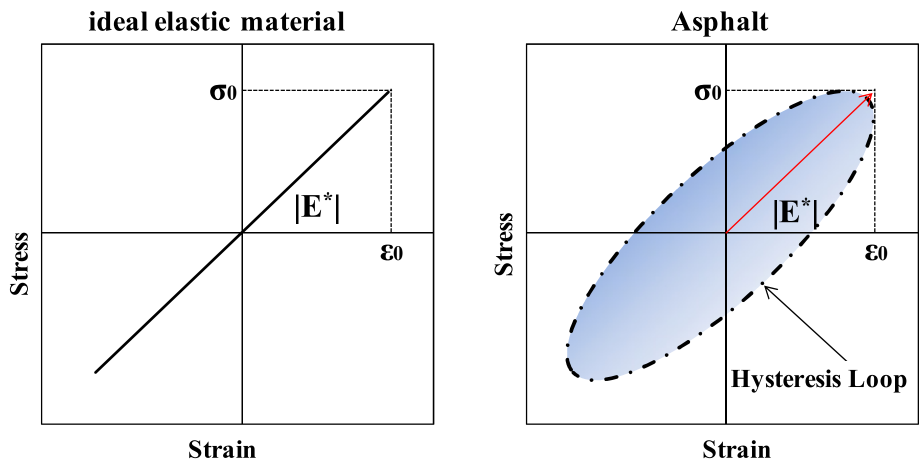

Figure C.6. One loading cycle in the strain-stress diagram for a perfectly elastic material (left), and for a viscoelastic material, such as asphalt (right).

The mechanical behaviour during cyclic loading is considered both in terms of strain and phase angle change (in stress-controlled test) during the material damage evolution. It is worth to mention that not all the dissipated energy in one loading cycle is responsible for material damage. Only a portion of the total energy that is dissipated is used for damaging the material (Ghuzlan and Carpenter, 2000).

Based on the concept of dissipated energy, the asphalt mixture recovery properties can be determined through a relative change in dissipated energy (ΔW, Equation C.2) between the beginning of Phase 1 (at the 100th cycle in Phase 1) and the beginning of Phase 2 (at the 100th cycle in Phase 2) of the test. By taking into consideration that dissipated energy in stress-controlled fatigue test increases (as a consequence of permanent material deterioration), ΔW can have negative values when the material mechanical properties are not completely recovered during the rest period. If, after the rest period, the material properties are the same as at the beginning of the tests, ΔW is equal to 0 %.

$$\Delta W = \frac{W_{100\_1} - W_{100\_2}}{W_{100\_1}} \cdot 100 \qquad [\%], \tag{C.2}$$

where: W_{100_1} = the dissipated energy at the 100th loading cycle in Phase 1 [kJ/m^3], W_{100_2} = the dissipated energy at the 100th loading cycle in Phase 2 [kJ/m^3].

A relative change in dissipated energy indicates the material capability of recovering its initial characteristics after the induced rest period. Relative recovery of the dissipated energy in the rest period can be caused by material healing, thixotropy and temperature decrease in the specimen (as a consequence of material heating during cyclic loading) (Di Benedetto et al., 2011).

C.3 Research results and analysis

The asphalt mixture recovery properties, prepared with bitumen having penetration grade of 50/70, were evaluated under rest periods of different durations. All tests were performed at temperature T = 20 °C with at least two test replicates. The results are presented in Table C.1 and Figure C.7.

Although all samples were loaded until the same drop of the complex modulus in Phase 1, computing the percentage difference between dissipated energy at the end and at the beginning of Phase 1 (at 100th cycle) it can be seen that the values are not consistent (see Table C.1). This is due to the different phase angle change during the cycle loading for each asphalt mixture.

Recovery capability of asphalt mixtures determined through relative change in dissipated energy (ΔW, Equation C.2) is highly dependent on the duration of the rest period, and it increases as the time for material recovery increases (see Figure C.7). Figure C.7 shows that beyond a certain rest period duration there is no influence on asphalt mixture recovery and a plateau stage is reached. Most likely, the recovery mechanism during this time is completed and any additional duration of the rest period does not affect recovery of the material. For the asphalt mixture used in this study, the plateau value is reached after approximately 14000 seconds.

Table C.1: Dissipated energy change in Phase 1 and relative change in dissipated energy between beginning of Phase 1 and beginning of Phase 2 (ΔW) as a function of the rest period duration and mixture composition

AC 11 D S with:	Rest period duration [s]	Dissipated energy change in Phase 1 [%]	Relative change in dissipated energy ΔW: beg. Phase 1, Phase 2 [%]
50/70	500	47.47	-17.04
	1000	57.23	-13.41
	7500	48.87	-0.57
	11000	56.80	0.18
	15000	48.16	4.43
	30000	50.00	2.98
25/55-55	1000	62.34	-14.23
50/70, aged		67.98	-20.91
50/70 with +0.5 M. -% Bin.		51.15	-7.39
50/70, high compaction		59.00	-11.73
50/70, low compaction		54.48	-12.18

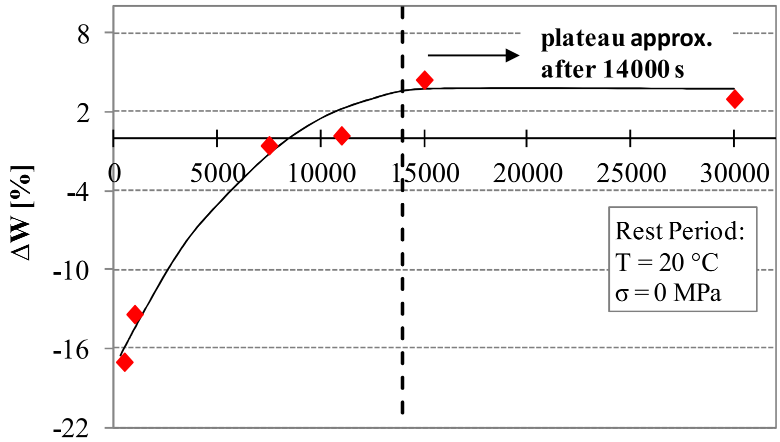

Figure C.7. AC 11 D S with 50/70 bitumen; Relative change in dissipated energy between beginning of Phase 1 and beginning of Phase 2 (Δ*W*) as a function of the rest period duration.

Figure C.7 shows that the dissipated energy changes when Δ*W* reaches values above 0 %. This implies that after the rest period, the specimen has better mechanical properties compared to beginning of the test. This can be explained by the fact that during the tension-compression loading in the initial loading phase (Phase 1), some structural changes occur in the material at 20 °C, which coupled with complete recovery induces slight improvements of material characteristics.

Small accumulated permanent strain occurred due to the specific tension-compression cycling loading applied in stress control (see Table C.2). Average recovery of the permanent strain during rest period from all the tests with AC 11 D S and 50/70 bitumen was 0.37 ‰. Complete recovery of the accumulated strain was observed after 11000 seconds rest period.

Table C.2: Recovery of the permanent strain during rest period and remaining accumulated permanent strain after rest period for AC 11 D S with 50/70 bitumen in uniaxial tension-compression fatigue test with different rest period durations

AC 11 D S with:	Rest period duration [s]	Recovery of permanent strain during rest period (average) [‰]	Remaining accumulated permanent strain after rest period (average) [‰]
50/70	500	0.21	0.51
	1000	0.31	0.52
	7500	0.54	0.17
	11000	0.48	0
	15000	0.34	0
	30000	0.36	0

Figure C.8 shows an example of the permanent strain evolution in one tension-compression fatigue test with a rest period of 7500 seconds.

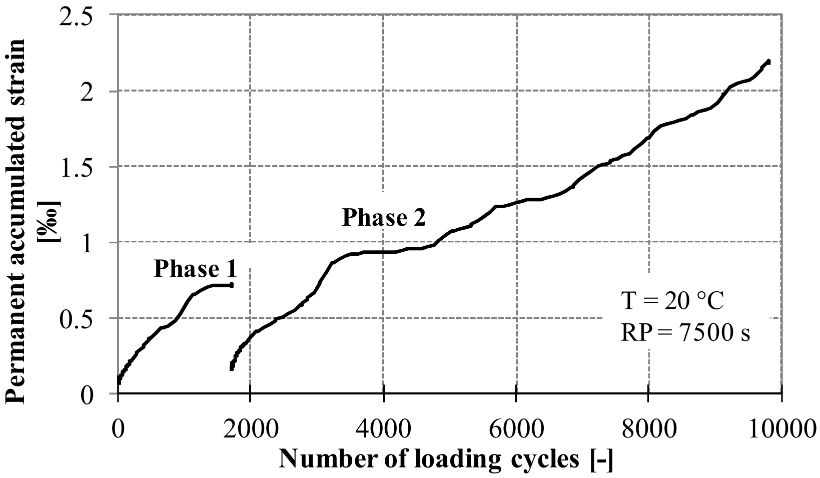

Figure C.8. Evolution of the accumulated permanent strain in cyclic tension-compression stress-controlled fatigue test with 7500 seconds rest period.

Analysis of the influences of material composition and specimen preparation on asphalt mixture recovery properties is performed using one rest period of 1000 seconds. This rest period duration is not related to the total recovery capability of asphalt mixtures; only the recovery capability at the early recovery stage is compared. Changes in the mix design were made in terms of bitumen type and amount. Mixture long-term ageing was also considered. Results are reported in Table C.1 and in Figure C.9.

Material recovery is extremely dependent on ageing. Aged samples show distinct lower ability to recover initial properties, which confirmed the theory from Little et al. (1999). Ageing makes the binder to be more brittle and more susceptible to fracture, as a consequence of higher asphaltene percentage.

With regard to bitumen type, mixture containing polymer-modified bitumen 25/55-55 shows relatively small changes in recovery behaviour, which was also observed by

Kim and Roque (2006). An explanation is given by Little et al. (1999), who hypothesized that the polymer acts as a filler system that interrupts the ability of pure bitumen to re-establish contacts and to heal.

Specimens prepared with additional 0.5 % bitumen by weight show the best recovery characteristics. This is most likely associated with a significant flow of bituminous mastic films that wet and partially close the initiated micro cracks.

The two degrees of compaction used in this study seem to have no significant influence on material ability to restore initial properties. It is assumed that after the lowest number of repetitions (10) the final asphalt structure is reached, and it does not significantly change with the application of additional passes.

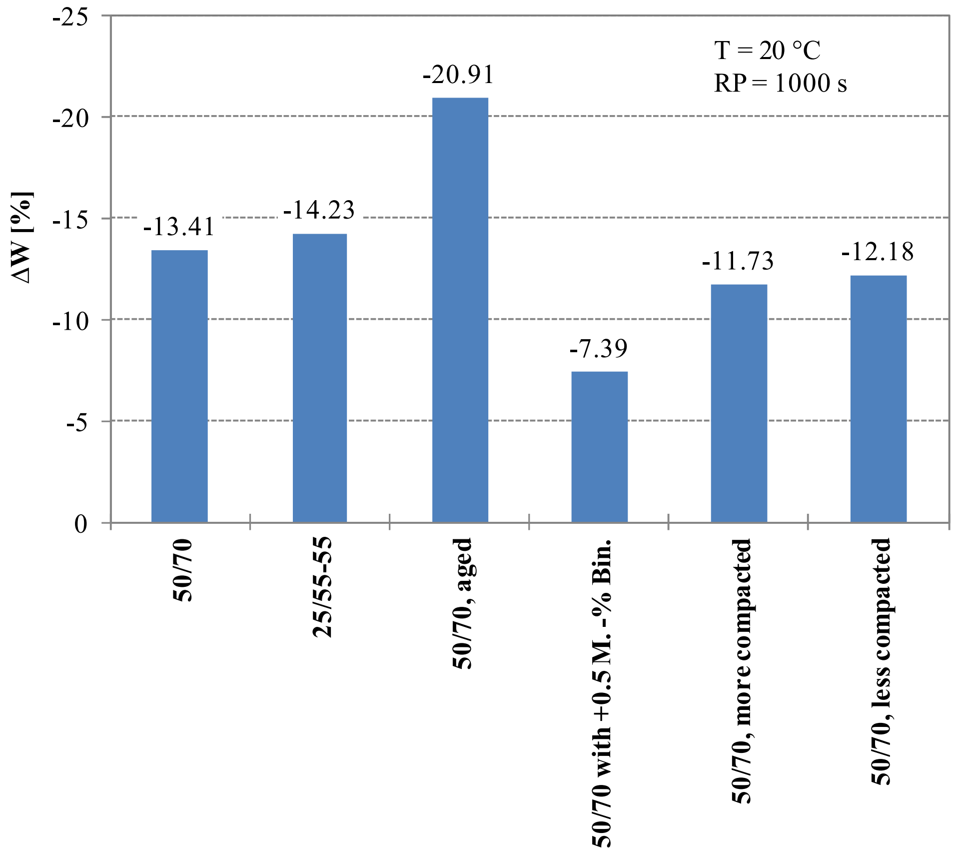

Figure C.9. Relative change in dissipated energy between beginning of Phase 1 and beginning of Phase 2 (ΔW) as a function of mixture composition after 1000 s rest period.

The present study shows that relative change in dissipated energy (ΔW) between the beginning of Phase 1 and the beginning of Phase 2 of the test can be equal to 0 %, meaning that after the rest period, complete recovery of asphalt mixture mechanical characteristics takes place. Based on recovery evaluation just at the beginning of Phase 2 it is not possible to state that the material behaviour after the rest period follows the same trend as in Phase 1. A test with a nearly 0 % ΔW (asphalt mixture with 50/70 bitumen with 7500 seconds rest period) is provided in Figure C.10, representing the evolutions of absolute values of complex modulus, phase angle and dissipated energy over the number of cycles. All parameters (complex modulus, phase angle and dissipated energy) recover during the rest period.

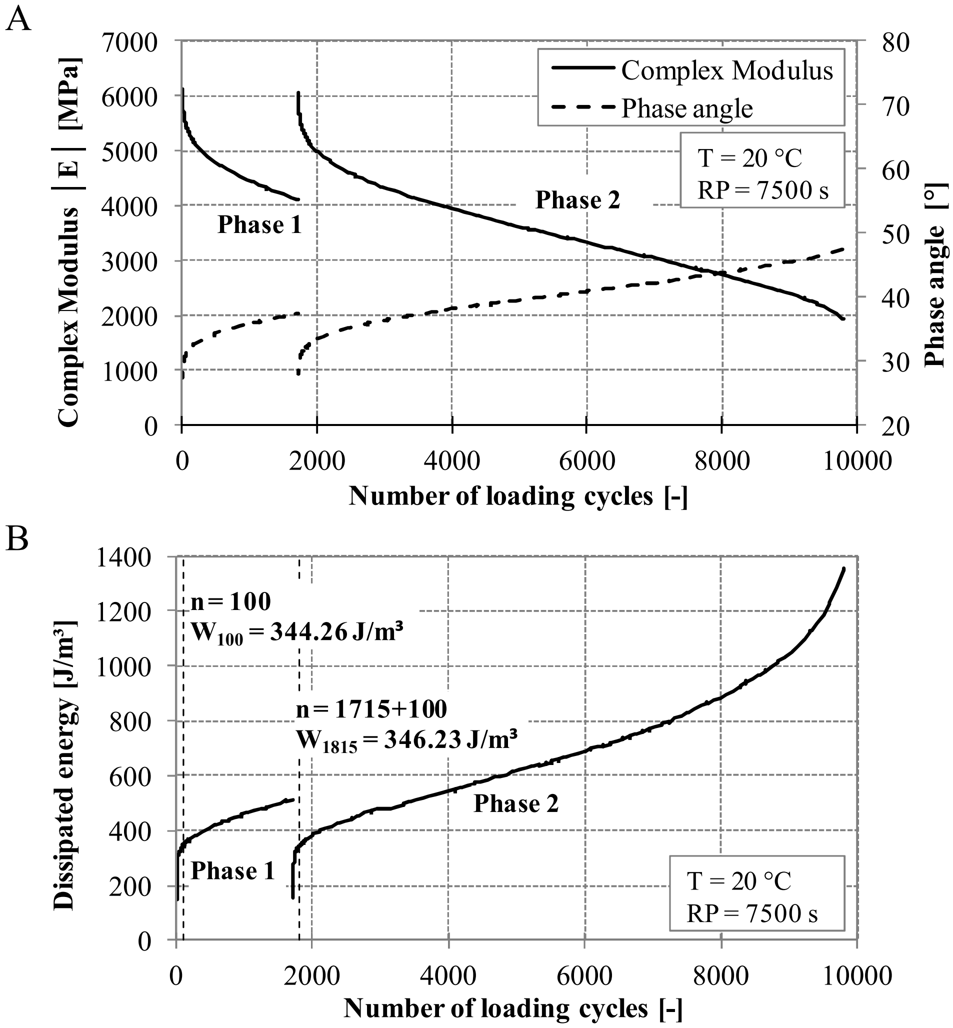

Figure C.10. Recovery test on asphalt mixture with 50/70 bitumen after 7500 seconds rest period. Evolutions of absolute values of complex modulus, phase angle (A) and dissipated energy (B) over the number of loading cycles.

The superposition of the complex modulus, phase angle and dissipated energy curves of Phase 1 and Phase 2 obtained by horizontal shifting of Phase 2 to the beginning of Phase 1 is presented in Figure C.11. The plot clearly shows that the evolutions of both values in Phase 2 correspond to the evolutions in Phase 1, which provides solid evidence of the complete recovery of asphalt mixture mechanical properties during the rest period. After the rest period the material behaves under loading like in the undamaged condition, and sustains nearly the same number of loading repetitions as in the first phase, until the same drop in complex modulus.

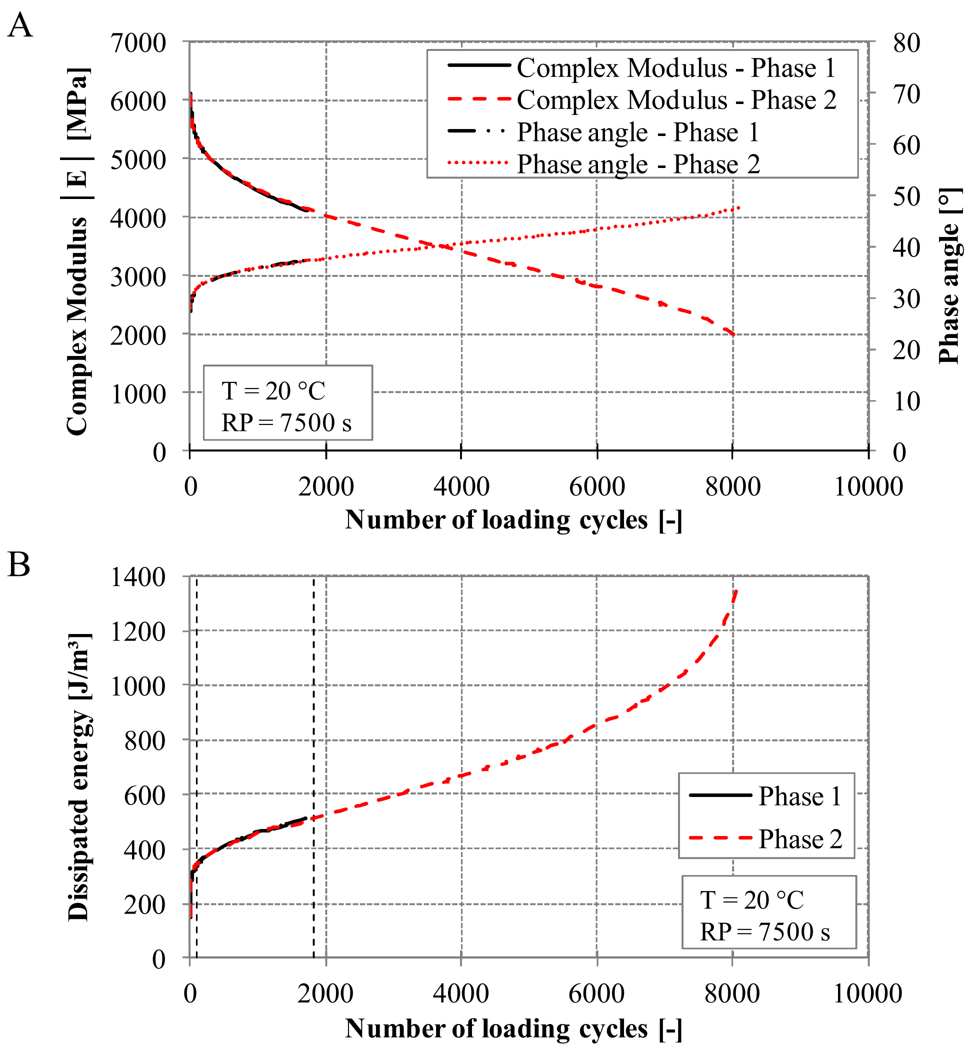

Figure C.11. Recovery test on asphalt mixture with 50/70 bitumen and with 7500 seconds rest period. Superposition of absolute values of complex modulus, phase angle (A) and dissipated energy (B) curves of the Phase 1 and Phase 2 over the number of loading cycles.

C.4 Conclusions and recommendations

In this study, the recovery properties of asphalt mixtures were studied based on fatigue stress-controlled uniaxial tension-compression test with rest period and analyzed based on the dissipated energy approach. For addressing the material recovery capability, a specific procedure was used; this takes into account the dissipated energy at the beginning of the initial loading phase and at the beginning of the loading phase after the rest period. The following conclusions can be drawn on the basis of the performed research work:

- Material recovery is highly dependent on the duration of the rest period in a way that with the increase in the rest period, the degree of recovery also increases.

- The impact of the rest period on asphalt mixture recovery capability is limited. After certain duration of the rest period there is hardly any influence on the material recovery and an asymptotic limit (plateau) is reached.

Material recovery, observed at early recovery stage (after 1000 seconds rest period), was compared for different mix designs:

- Material recovery decreases with material ageing, since the aged binder is more brittle and more susceptible to fracture (as a consequence of the higher asphaltene content).
- Polymer-modified bitumen showed a relatively small change in recovery behaviour compared to plain bitumen. More research and different polymer modifications need to be investigated in order to further support the findings on the impact of polymers on material recovery.
- Specimens prepared with additional 0.5 % bitumen by weight show the best recovery characteristics compared to others. This can be explained by higher flow processes of the bituminous mastic film that positively influences closing of the initiated micro cracks.
- The degree of compaction used in this investigation seems to have no significant influence on material ability to restore its initial properties. It is assumed that after the lowest number of rolling repetitions in the segmented steel roller compactor, the final asphalt structure is reached, and it does not change significantly with the application of additional roller passes. Therefore, no change in asphalt mixture recovery properties was identified.

Additional research is nevertheless needed in order to discriminate the specific effects which drive the material recovery during rest periods. The temperature effects inside the tested specimen, nonlinearity and thixotropy effects need to be better understood in order to evaluate pure material recovery.

C.5 References

Bell, C. 1989. Summary report on ageing of asphalt-aggregate systems (SHRP-A/IR-89-004). Project A-003A (Performance Related Testing and Measurement of Asphalt-Aggregate Interactions and Mixtures), Strategic Highway Research Program, National Research Centre, Washington, D.C.

Büchler, S., Mollenhauer, K.,Wistuba, M., and Renken, P. 2009. Aging of stone mastic asphalt and evaluation of cracking resistance. In E. Tutumluer and I. L. Al-Qadi (Eds.), Bearing capacity of roads, railways and airfields, pp. 339-348.

Carpenter, S., and Shen, S. 2006. A dissipated energy approach to study HMA healing in fatigue. Transportation Research Record (TRR): Journal of the Transportation Research Board, 1970, pp. 178-185.

Di Benedetto, H. 2013. Fatigue and other phenomena during cyclic loading of bituminous materials. Keynote at Int. EATA Conf., Jun. 3-5, 2013, Braunschweig, Germany.

Di Benedetto, H., Nguyen, Q. T., and Sauzeat, C. 2011. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 12(1), pp. 129-158.

Ghuzlan, K., and Carpenter, S. 2000. An energy-derived, damage-based failure criteria for fatigue testing. Transportation Research Record, Journal of the Transportation Research Board, No. 1723, pp. 141-149.

Kim, B., and Roque, R. 2006. Evaluation of healing property of asphalt mixtures. Transportation Research Record, Journal of the Transportation Research Board, No. 1790, pp. 84-91.

Little, D. N., Lytton, R. L.,Williams, D., and Kim, Y. R. 1999. An analysis of the mechanism of microdamage healing based on the application of micromechanics first principles of fracture and healing. Asphalt Paving Technology, pp. 501-537, Chicago, USA.

Luo, X., Luo, R., and Lytton, L. 2013. Characterization of recovery properties of asphalt mixtures. Journal of Construction and Building Materials, Vol. 48, pp. 610-621.

Renken, P. 2000. Influence of specimen preparation onto the mechanical behaviour of asphalt aggregate mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, pp. 729-735, Sept. 20-22, 2000, Barcelona, Spain.

Shen, S., Chiu, H., and Huang, H. 2009. Fatigue and healing in asphalt binders. CD-ROM. Transportation Research Board Meeting, Washington, DC.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

D Experimental study on asphalt mixture recovery[4]

Abstract: Asphalt materials used in road pavements are exposed to repeated heavy traffic loading under changing climates. These phenomena make pavements prone to fatigue deterioration as a consequence of the formation of micro-cracks, which can coalesce into a network, ultimately leading to macro cracking and structural collapse. Susceptibility of asphalt mixtures to fatigue is usually evaluated through cyclic laboratory testing, where asphalt specimens are subjected to sinusoidal loading cycles. As the number of cycles increases, a significant loss in material stiffness occurs. However, if loading is interrupted by introducing a rest period between two continuous loading phases, an important change in material behavior is observed. This is associated with a substantial stiffness recovery, which in turn triggers the material's fatigue life. In this study, the phenomenon of stiffness recovery during rest periods is investigated. Cyclic uniaxial tension-compression loading tests are conducted in stress-control mode and rest periods of different durations are considered. Dissipated energy is analyzed and used to assess the material's capability for recovery and a new recovery index is proposed. It is found that the newly developed index can successfully assess the recovery properties of asphalt mixture.

Keywords: material recovery, fatigue, recovery index, rest period.

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[4] Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Experimental study on asphalt mixture recovery. Published in Journal of Materials and Structures, Vol. 50:196, pp.1-9, DOI: 10.1617/s11527-017-1064-0, Springer.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 85 %

D.1 Introduction

Heavy traffic and climate loading induce a repeated and cyclic state of stress in asphalt pavements, weakening the material, while leading to detrimental fatigue phenomena. During loading, a micro crack network forms which after an additional number of loading cycles, may coalesce into visible macro cracks, eventually leading to premature failure, and significantly reducing pavement durability.

As pavement structures are not continuously loaded, a certain degree of recovery is possible during non-loading phases (i.e. between two consecutive vehicle load application), while cracks have the opportunity of partially or entirely closing. This phenomenon is commonly known as self-healing. Self-healing is defined as the materials recovery capability under certain loading and environmental conditions, especially during rest periods (Shen et al., 2009). It is assumed that the self-healing potential extend the durability of asphalt pavements, since asphalt materials with high recovery capabilities accumulate less deformation and less damage in the asphalt layers (Luo et al., 2013).

Susceptibility of asphalt pavement materials to fatigue cracking and self-healing capabilities are usually evaluated through cyclic laboratory tests on asphalt mixture specimens, with and without application of rest period(s) (Breysse et al., 2003; Carpenter and Shen, 2006). During a fatigue test, a significant loss in material stiffness is observed as the loading cycles increase. If loading is interrupted during the test by introducing a rest period between two continuous loading phases, a substantial recovery of the material stiffness is observed. Due to the reversed stiffness behavior, a significant extension of the material's fatigue life is expected. This stiffness recovery is usually ascribed to the self-healing properties of the mixture. Recent findings have shown that the stiffness recovery during the rest period is not a consequence only of self-healing, but is coupled to additional phenomena, including self-heating, thixotropy, and non-linearity (Di Benedetto et al., 2011; Mangiafico et al., 2015). Therefore, using the term ''recovery'' in place of ''self-healing'' appears to be more accurate and comprehensive.

Self-healing, or rather recovery capability of asphalt binder and asphalt mixtures properties, has been investigated by many researchers, both at the micro and macro scale (Breysse et al., 2003, Carpenter and Shen, 2006; Di Benedetto et al., 2011; Daniel, 1996; Phillips, 1998; Little et al., 1999; Bodin et al., 2004; Kim and Roque, 2006; Bhasin et al., 2009; Santagata et al., 2009; Kringos et al., 2011; Nazzal at al., 2012; Palvadi et al., 2012; Tan et al., 2012; Shan et al., 2013; Santagata et al., 2013; Moreno-Navarro et al., 2015; Ayar et al., 2016). In these studies a high dependency of binder and mixture recovery potential was observed and linked to specific materials properties (composition, binder viscosity, air voids content and mechanical characteristics) and external conditions (testing configuration, temperature, loading and rest period duration). However, due to the large scatter of the experimental results observed for both continuous and discontinuous (with rest periods) fatigue tests, few effort has been put on the derivation of an effective recovery index applicable for the evaluation of the recovery potential of specific asphalt mixture.

D.2 Background

The investigation of the recovery potential of asphalt mixture is commonly experimentally addressed through dynamic tests based on cyclic sinusoidal loading followed by one or more rest periods applied to specimens in different testing configurations. Two different approaches for introducing rest period(s) can be identified (Shen and Carpenter, 2007):

- a single rest period after a pre-defined number of loading cycles, or
- a single rest period after every loading cycle.

The first method simulates the loading conditions in the field in a less realistic manner, as on the road rest periods of different durations occur randomly. However, in laboratory, this method provides clear insight into the variation of material properties in consequence of a single rest period, as demonstrated in recent studies (Wistuba et al., 2013; Isailović et al., 2016). Therefore, this study uses the first approach.

When evaluating the recovery potential of a specific asphalt mixture, the fatigue life resulting from a cyclic test with rest period(s) is usually compared to a test with same loading conditions, but without rest period(s). Consequently, a significant difference in fatigue lives between the two tests indicates a high recovery potential for the specific asphalt mixture.

Figure D.1 exemplarily shows the result of a discontinuous fatigue test (recovery test) for a rest period duration of 7500 seconds introduced after 1800 loading cycles (solid line), and the results of continuous fatigue tests (dashed lines), for an asphalt surface course material (Wistuba et al., 2013). These tests were conducted on prismatic asphalt mixture specimens in tensile-compressive stress control mode and for pre-defined loading conditions (test temperature 20 °C; stress amplitude 1.05 MPa). It is noted, that considering the number of loading cycles at failure (N_f) (here i.e. the number of loading cycles, where the complex modulus has decreased by 50 % of its initial value) (Di Benedetto et al., 2004), a high scatter of the results from continuous tests is observed, resulting in a difference between shortest and longest fatigue lives of 71 %. Even though all test specimens were made of the same asphalt mixture subjected to the same compaction procedure, it is hypothesized that the structural characteristics of the individual test specimens, like aggregate orientation, contact points, contact lengths, may induce significant differences in mechanical material behavior (Sefidmazgi et al., 2012). This makes interpretation of tests and evaluation of recovery properties even more challenging.

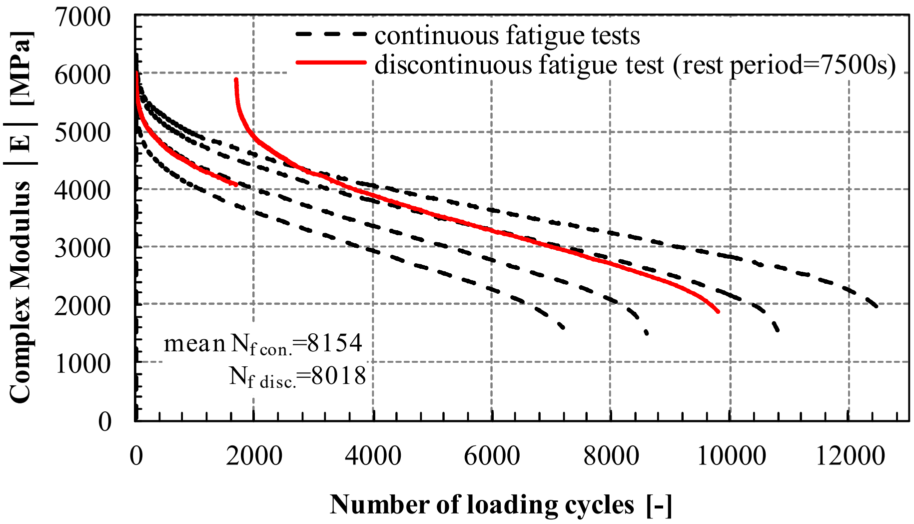

Figure D.1. Evolution of complex modulus as function of number of loading cycles in continuous and discontinuous uniaxial tension-compression fatigue tests in stress control mode at a temperature of 20 °C and stress amplitude of 1.05 MPa (Wistuba et al., 2013).

Such a large scatter in the results may lead to erroneous evaluation of recovery potential, especially when a recovery index of the following type is used (*RI*, Equation D.1), which compares the fatigue lives of continuous and discontinuous fatigue tests based on the number of loading cycles until fatigue failure (cp. Santagata et al., 2009; Little et al., 2001; Van den Bergh and Van der Ven, 2012):

$$RI = \frac{N_{f\,disc.} - N_{f\,con.}}{N_{f\,con.}} \cdot 100 \qquad [\%], \tag{D.1}$$

where $N_{f\ dics.}$ = number of loading cycles at failure in discontinuous fatigue test [-], $N_{f\,con.}$ =number of loading cycles at failure in continuous fatigue test [-].

For the values of data represented in Figure D.1 ($N_{f\ disc.}$ = 8018, $N_{f\ con.}$ = 8154), Equation D.1 leads to a recovery index of *RI* = -1.67 %. Hence, a negative recovery potential is calculated, which is unreasonable as the full recovery is observed after a rest period of 7500 seconds (see Figure D.1). Therefore, a more consistent, effective and reliable approach is needed, to overcome the biasing effects originating from the tremendous scatter of the experimental results.

D.3 Objective and research approach

The objective of this study is to develop a new recovery index, which can substantially and successfully mitigate the material-related scatter observed in the experimental results of continuous fatigue tests. For this purpose, uniaxial tension-compression tests were conducted on prismatic specimens in stress controlled mode. Continuous and discontinuous fatigue tests with single rest periods of different duration were performed to investigate the asphalt mixture recovery properties. The analysis of recovery potential is based on the dissipated energy approach (Hopman et al., 1989). Finally, a newly developed recovery index is proposed and validated. Figure D.2 provides a flow chart of the selected research approach.

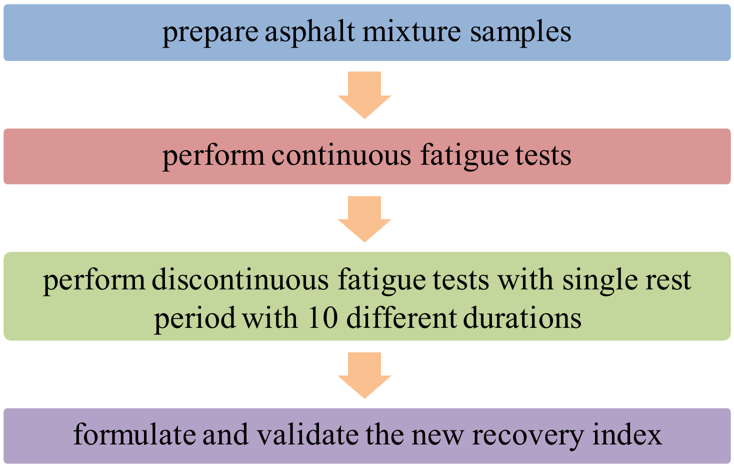

Figure D.2. Flow chart of the research program.

D.4 Experimental study

D.4.1 Material and fabrication of asphalt mixture specimens

In this experimental study asphalt mixture, identified as AC 11, was prepared (Asphalt Concrete - AC, maximum grain size of 11 mm, 5.6 mass % of plain asphalt binder 50/70). This mixture is commonly used for surface course layers on highly trafficked asphalt pavements. Figure D.3 represents the aggregate gradation curve.

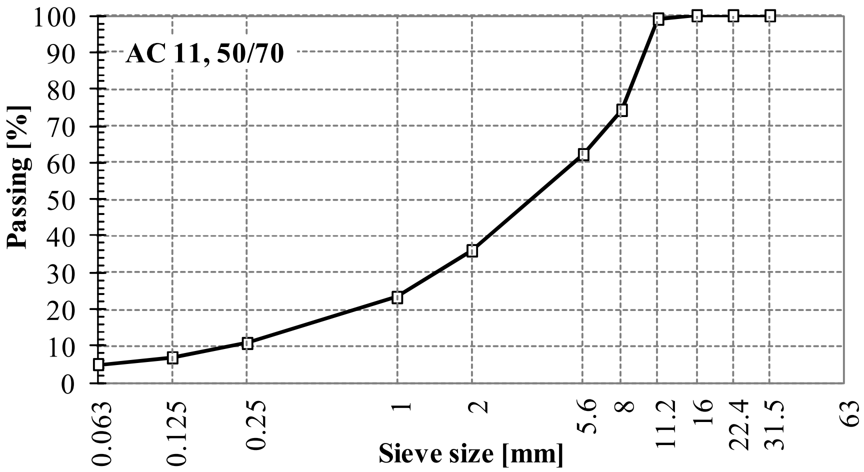

Figure D.3. Aggregate gradation curve of asphalt mixture of the type AC 11 (Asphalt Concrete - AC, maximum grain size of 11 mm, 5.6 mass % of plain asphalt binder 50/70).

Asphalt mixture slabs having dimensions 320 × 200 × 75 mm^3 were prepared using segmented steel roller compaction method. The compactor is composed of a mould to hold the asphalt mixture and a cylindrical steel sector to induce a kneading action and to apply a vertical force to the mixture (Wistuba, 2014).

From the slabs, prismatic specimens were cut with final dimensions of 50 × 50 × 160 mm^3 and having average air voids contents of 5.5 %.

D.4.2 Testing

Strain field measurements on asphalt pavements have demonstrated that both tensile and compressive stresses may occur in one point of pavement due to wheel loading (Wistuba and Perret, 2004; Rabe, 2008). From an experimental point of view, the presence of both stress states, tension and compression, in stress-controlled fatigue tests leads to most distinct change in mechanical properties (Isailović et al., 2015 a). For this reason, the uniaxial stress-controlled tension-compression fatigue test was selected for the present study. Figure D.4 represents the test setup.

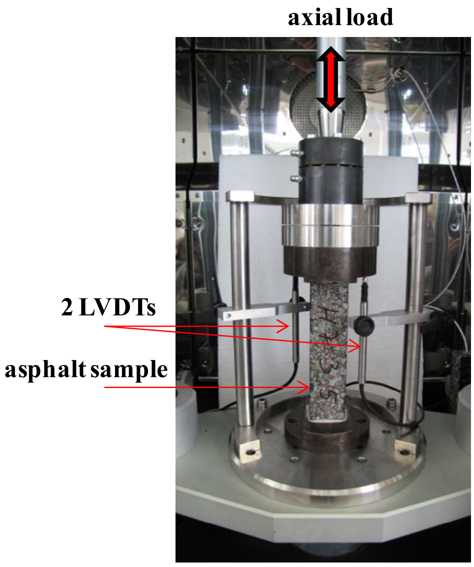

Figure D.4. Test setup used in the present research.

During the test, a vertical stress amplitude is applied, and the resulting deformation is measured using two analog strain transducers (LVDT, linear variable differential transformer), attached to both sides of the test specimen (see Figure D.4). An example of stress-strain-amplitude evolution is shown in Figure D.5. After 30 initial load cycles, the stress amplitude was held at a constant level until failure. For both LVDT, the strain increase always followed the same trend on both sides of the specimen.

The prismatic asphalt specimens (50 × 50 × 160 mm^3) were subject to a sinusoidal cyclic load in tension and compression with a stress amplitude of 0.7 MPa, at a frequency of 10 Hz and at a temperature of 20 °C.

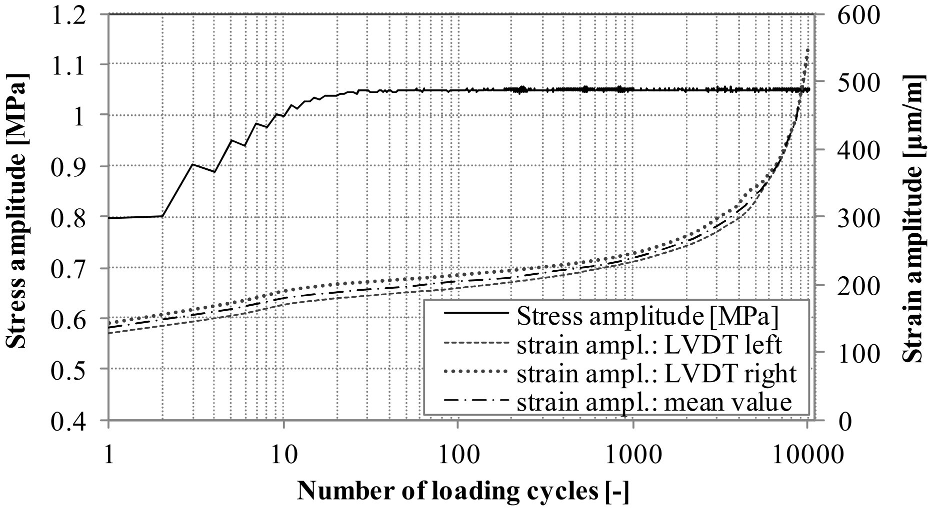

Figure D.5. Evolutions of stress-amplitude and strain-amplitude in cyclic tension-compression stress-controlled fatigue test (at temperature 20 °C and stress amplitude 1.05 MPa).

Stress, displacement and temperature were monitored and recorded during the entire test. Based on test results, the absolute value of complex modulus $|E_n|$ was calculated as follows:

$$|E_n| = \frac{\sigma_{0,n.}}{\varepsilon_{0,n.}} \qquad [\text{MPa}], \tag{D.2}$$

where $\sigma_{0,n}$ = stress amplitude in cycle n [MPa], $\varepsilon_{0,n}$ = strain amplitude in cycle n [-].

In order to assess the number of load repetitions at failure, an approach based on the energy ratio (*ER*) proposed by Hopman et al. (1989) was used for both continuous and discontinuous tests. This failure criterion relies on dissipated energy which is a good criterion for observing material behavior during cyclic loading (Carpenter and Shen, 2006). The energy ratio (*ER*) represents the ratio between the initial dissipated energy, and the dissipated energy at cycle *n*, reading

$$ER = \frac{n \cdot W_0}{W_n} \qquad [-], \tag{D.3}$$

where n = cycle number [-], W_0 = initial dissipated energy (for 100th cycle) [kJ/m^3], W_n = dissipated energy at cycle n [kJ/m^3].

The dissipated energy (W_n) in one load cycle can be calculated from:

$$W_n = \pi \cdot \sigma_n \cdot \varepsilon_n \cdot sin\varphi_n \qquad [\text{kJ/m}^3], \tag{D.4}$$

where: σ_n = stress amplitude at cycle n [MPa], ε_n = strain amplitude at cycle n [‰], φ_n = phase angle at cycle n [°].

A typical example of energy ratio evolution is shown in Figure D.6. By plotting the energy ratio versus the number of loading cycles, the resulting fatigue life is defined as the number of loading cycles when *ER* reaches its maximum. The corresponding number of cycles, N_{Macro}, provides the point of transition from micro to macro cracking.

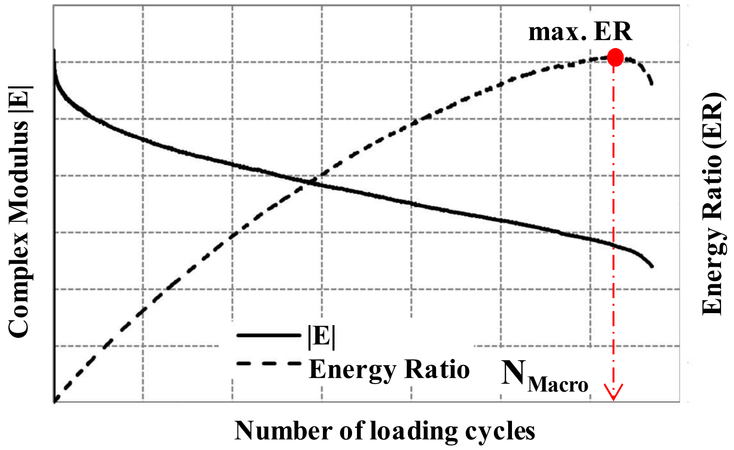

Figure D.6. Typical evolutions of the complex modulus and of the energy ratio in function of the number of loading cycles in a uniaxial tension-compression fatigue test.

D.5 Recovery index

D.5.1 Normalized energy ratio

In order to address the recovery potential of the asphalt mixture, continuous and discontinuous fatigue tests with single rest period were compared. As specified in the previous section, both types of test were performed with the same loading conditions.

The results of continuous fatigue tests are presented in Figure D.7, where a high scatter in fatigue life is observed. The difference between shortest and longest fatigue life exceeds 37 % (corresponding to N_{Macro} = 46139 and N_{Macro} = 63645).

To overcome such a limitation the experimental values were normalized using the reference value, E_0 = 100 %, where E_0 is the absolute value of the initial complex modulus (calculated at 100th cycle). The normalized values of complex modulus were then plotted against the normalized values of the energy ratio (reference value: ER_{100} = 100 %, where ER_{100} is a peak value of energy ratio) for all the continuous tests presented in Figure D.7, showing a consistent trend which follows almost the same curve (see Figure D.8). This leads to the conclusion: when fatigue tests are performed under the same loading conditions, a unique representative fatigue curve can be found, no matter how many cycles the asphalt sample experiences at failure. Similar findings were observed for other asphalt mixtures and test conditions: AC 11 and AC 16 mixtures with different binder contents and binder sources, and compaction mode (Wistuba et al., 2013).

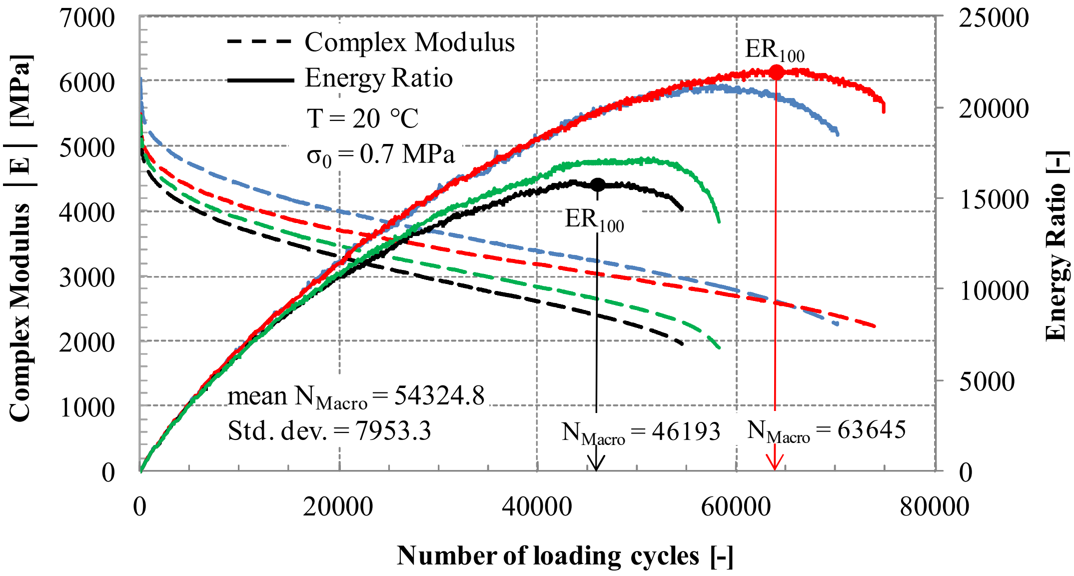

Figure D.7. Evolutions of complex modulus and energy ratio in function of number of loading cycles in continuous uniaxial tension-compression fatigue tests (at temperature 20 °C and stress amplitude 0.7 MPa).

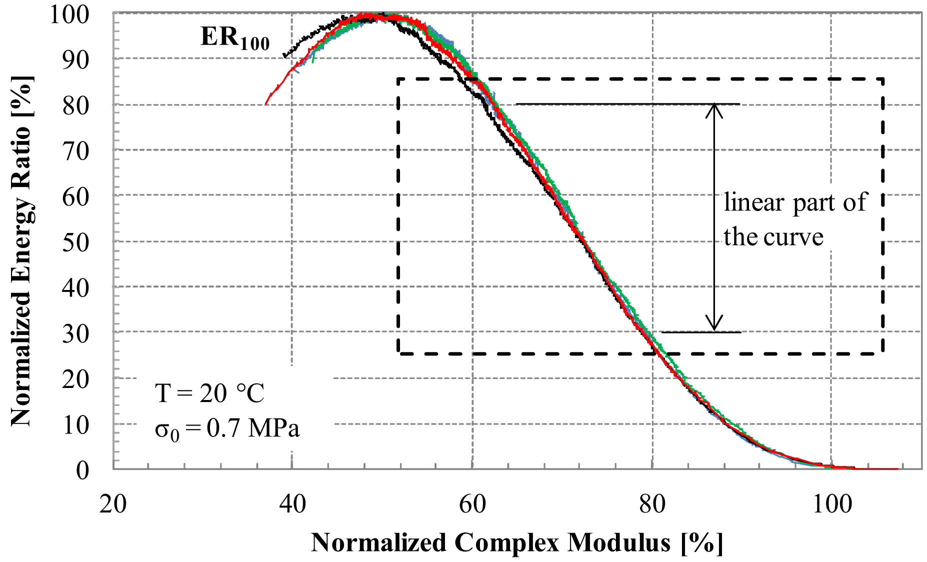

Figure D.8. Evolutions of normalized energy ratio-complex modulus curves for continuous uniaxial tension-compression fatigue tests presented in Figure D.7.

Restricting attention to the normalized value of energy ratio between 30 and 80 % an almost linear pattern was found. Therefore, it was hypothesized that a unique trend can be assumed for all tests conducted at the same loading conditions (Figure D.9). This characteristic can be used for evaluating the recovery potential of asphalt mixtures as explained hereafter.

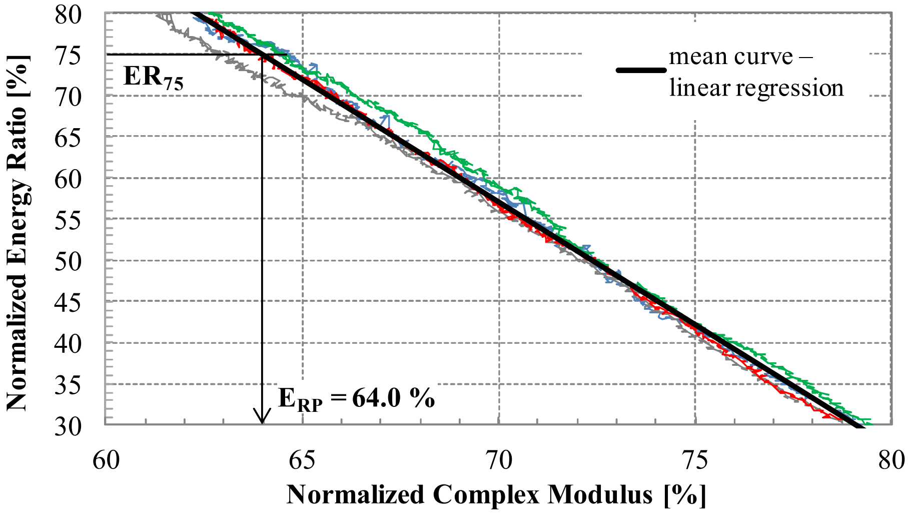

Figure D.9. Evolutions of normalized energy ratio-complex modulus curves and with linear regression approximated mean value in part between 30 and 80 % of the normalized energy ratio for continuous uniaxial tension-compression fatigue tests presented in Figure D.7.

D.5.2 Formulation of the new recovery index

The effect of rest period on asphalt mixture recovery potential was studied through variation of rest period durations: 500, 1000, 2000, 3000, 7500, 11000, 20000, 30000, 45000, and 86400 seconds. For each rest period duration, at least three test repetitions were performed.

The rest period was always introduced after the material reached 75 % of its maximum energy ratio, or a corresponding decay of the complex modulus down to the E_{RP} = 64 % (see Figures D.9, D.10). According to Di Benedetto et al. (2004), at this point, the decrease of the complex modulus is mostly affected by fatigue, and not by biased effects of nonlinearity, heating and thixotropy like in the initial loading phase. Therefore, the material recovery is influenced by self-healing too. During the rest period, the specimen was stress free. After the rest period, the specimen was loaded again, with a new loading phase until failure (loading phase 2, Figure D.10).

From the evolution of the normalized energy ratio-complex modulus curve (Figure D.9), which can be assumed as a unique representative fatigue curve for the specific asphalt mixture and test conditions, it is possible to estimate with good approximation the maximum value of the energy ratio (ER_{100}) for the extended first loading phase without rest period (represented as the continuous fatigue test, dashed red line in Figure D.11):

$$|ER_{100}| = ER_{75} \cdot \frac{100}{75} \quad [-], \tag{D.5}$$

where: ER_{75} = energy ratio at the end of loading phase 1 (specimen is loaded until 75 % of maximum energy ratio) [-], ER_{100} = calculated maximum energy ratio for continuous fatigue tests [-].

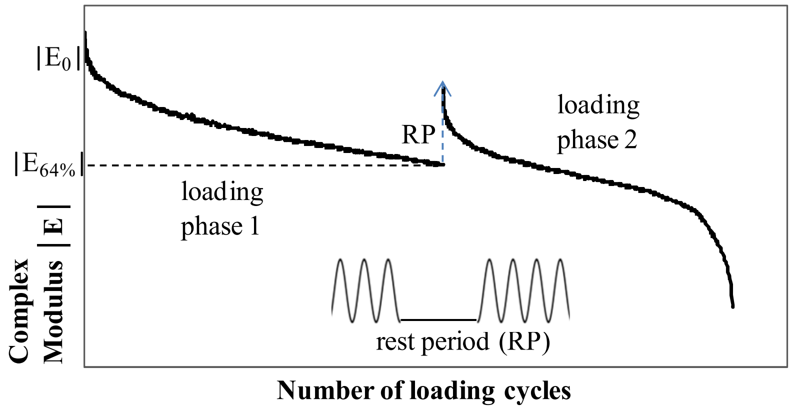

Figure D.10. Test protocol used to study the recovery potential: loading phase 1 + rest period + loading phase 2 (schematic).

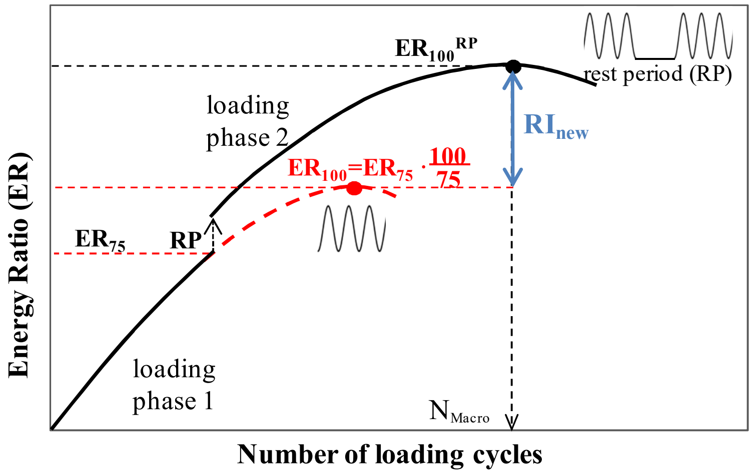

Figure D.11. Estimating the recovery index from the evolution of energy ratios in the loading phase 1 and in the loading phase 2 (schematic).

This approach gives the possibility to compare the maximum energy ratio from tests with rest period, ER^{RP}_{100}, (Figure D.11) to the calculated energy ratio from continuous tests, ER_{100}, (Figure D.11), obtained from the same asphalt mixture specimen. The relative difference between these two values represents the new recovery index (RI_{new}), reading

$$RI_{new} = \frac{ER^{RP}_{100} - ER_{100}}{ER_{100}} \cdot 100 \quad [\%], \tag{D.6}$$

where: ER^{RP}_{100} = maximum energy ratio from the test with rest period [-], ER_{100}=calculated maximum energy ratio for continuous fatigue test [-].

The principle of estimating the recovery index from the evolution of energy ratios in the first and the second loading phase is illustrated in Figure D.11. The higher the increase in energy ratio, the higher is the material recovery capacity. The significant advantage of proposed procedure consists in the possibility of estimating the recovery potential on just one asphalt sample, which can drastically reduce the results scattering, as well as the tremendous time demanding experimental campaign required by fatigue testing.

D.5.3 Results and validation

The recovery index was studied for rest periods of different durations. Based on previous research results, recovery potential of asphalt mixture increases with increased rest period duration (cp. Carpenter and Shen, 2006; Palvadi et al., 2012; Isailović et al., 2015 b).

Figure D.12 illustrates the evolution of complex modulus for a rest period duration of 30000 seconds. A distinct recovery of the complex modulus is observed resulting in complex modulus almost at the same level of the loading phase 1. This is a good indicator for an extended fatigue life.

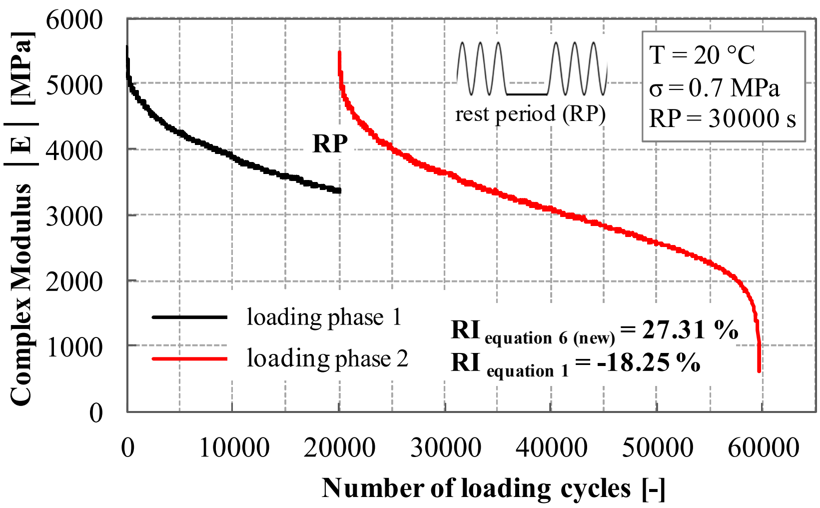

Figure D.12. Evolution of absolute value of complex modulus at a rest period duration of 30000 seconds.

The mean values of the new recovery index calculated for the different rest period durations are given in Table D.1 and Figure D.13.

For the purpose of comparison, the results for recovery index calculated from Equation D.1 are also reported.

The analysis has shown that the introduced recovery index (Equation D.6) increases when rest period duration increases, allowing for a successful assessment of the recovery properties. Beyond a certain rest period duration there is no influence on the recovery capacity of the asphalt mixture and a plateau stage is reached (here after approximately 45000 seconds). Similar results were observed in work of Maillard et al. (2004) on binder level. Coefficients of variation are relatively low, indicating reliable test repeatability.

Table D.1: Mean values and standard deviations of the new recovery index calculated from Equation D.6 and for the recovery index calculated from Equation D.1 for different rest period durations

rest period duration [s]	new *RI* from Equation D.6 [%]		*RI* from Equation D.1 [%]	
	mean value	coefficient of variation	mean value	coefficient of variation
500	2.22	0.71	7.71	4.23
1000	8.03	0.31	60.78	0.32
2000	13.06	0.01	51.16	0.50
3000	13.99	0.08	29.99	0.09
7500	18.70	0.03	17.71	2.39
11000	23.05	0.14	41.83	0.96
20000	29.38	0.16	67.35	0.25
30000	28.97	0.08	4.75	6.84
45000	33.91	0.1	-21.99	0.52
86400	31.68	0.12	27.77	1.93

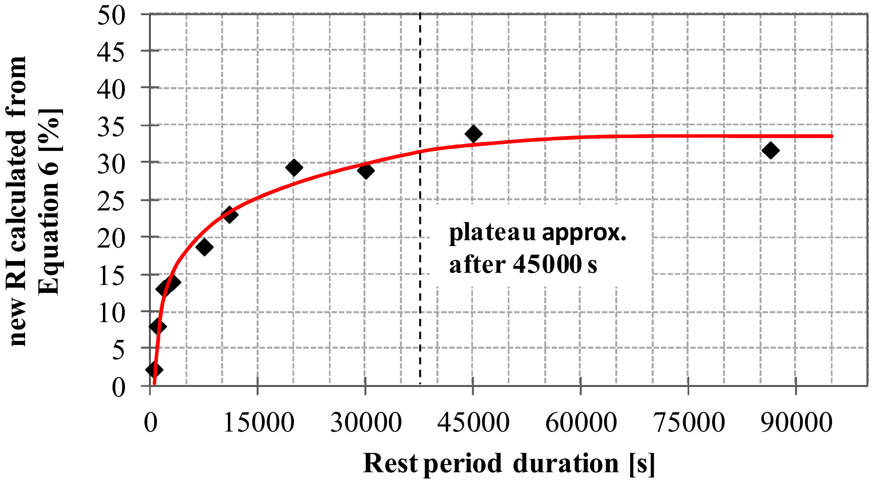

Figure D.13. Mean values of the new recovery index (*RI*) calculated from Equation D.6 for different rest period durations.

In contrary, the recovery index calculated from Equation D.1 does not show any reliable dependence from rest period duration (see Figure D.14). The deviations between single tests are relative high, showing for some specimens considerably negative values, although almost a full recovery of the mechanical properties as observed during the rest period (cp. Figure D.12, $RI_{equation\ D.1}$ = -18.25 %).

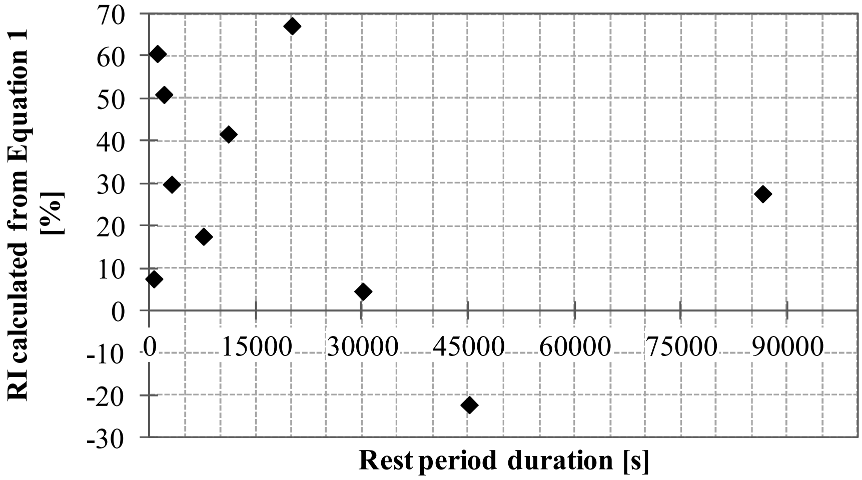

Figure D.14. Mean values of the recovery index calculated from Equation D.1 for different rest period durations.

D.6 Conclusions

Recovery properties of a conventional asphalt mixture were investigated based on the dissipated energy approach. For this purpose, the uniaxial tension-compression test in controlled-stress mode was used with and without rest periods.

A new recovery index is proposed to quantify the recovery potential of asphalt mixtures. It is based on continuous fatigue tests and discontinuous fatigue tests with a single rest period, by using one asphalt mix specimen for both tests only. The new procedure excludes material-related result scatter from continuous tests, which are used as a basis for the recovery calculation. This was achieved using a unique normalized energy ratio-complex modulus curve that for all conducted continuous fatigue tests follow almost the same trend, no matter how many loading cycles the asphalt specimen experienced at failure.

Validation of the recovery index was performed introducing different durations of the rest period (from 500 to 86400 seconds). It was found that the new recovery index increases as the rest time increases, allowing for the successful assessment of the recovery properties. On the other side, the result scattering is significantly reduced, indicating a good test repeatability. Based on these findings, the developed recovery index is judged as an appropriate tool for recovery evaluation and it can be used for pre-selection of pavement materials, and can be seen as a key performance indicator for pavement durability.

More research in this field is needed in order to distinguish the effects which drive the material recovery during the rest period and to examine ‘‘pure’’ self-healing properties. Among concurrent factors, temperature evaluation has to be monitored in order to exclude temperature effects, while a better understanding of thixotropy effects is needed.

D.7 References

Ayar, R., Moreno-Navarro, F., and Rubio-Gamez, C. 2016. The healing capability of asphalt pavements: a state of the art review. Journal of Cleaner Production, Vol. 113, pp. 28-40.

Bhasin, A., Narayan, A., and Little, D. 2009. Laboratory investigation of a novel method to accelerate healing in asphalt mixtures using thermal treatment. Research report SWUTC/ 09/476660-00005-1, University of Texas, Austin, USA.

Bodin, D., Soenen, H., and De La Roche, C. 2004. Temperature effects in binder fatigue and healing tests. Proc., 3rd Eurasphalt and Eurobitume Congress, Book II, pp. 1996-2004, May 12-14, 2004, Vienna.

Breysse, D., De La Roche, C., Domec, V., and Chauvin, J.J. 2003. Influence of rest time on recovery and damage during fatigue tests on bituminous composites. Journal of Materials and Structures, Vol. 36, pp. 648-651.

Carpenter, S., and Shen, S. 2006. A dissipated energy approach to study HMA healing in fatigue. Transportation Research Record (TRR): Journal of the Transportation Research Board, No 1970, pp. 178-185.

Daniel, JS. 1996. Rate dependent stiffness of asphalt concrete used for field to laboratory prediction and fatigue and healing evaluation. M.Sc. Thesis, North Carolina State University, Raleigh.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundström, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Di Benedetto, H., Nguyen, Q-T., and Sauzéat, C. 2011. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 12(1), pp. 129-158.

Hopman, P., Kunst, P., and Pronk, A. 1989. A renewed interpretation model for fatigue measurement. Verification of Miner´s rule. Proc., 4th Eurobitumen Symposium, Oct. 4-6, 1989, Madrid.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 a. Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests. Proc., 8th International RILEM SIB symposium, Vol. 11, RILEM Bookseries, pp. 693-709, Oct. 7-9, 2015, Ancona, Italy.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 b. Asphalt recovery properties in fatigue test with single rest period. Proc., 6th international conference - bituminous mixtures and pavements, Jun. 10-12, 2015, Thessaloniki, Greece.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2016. Characterization of asphalt mixture recovery properties based on dissipated energy approach. International Society for Asphalt Pavements Symposium, Jul. 18-22, 2016, Jackson Hole, Wyoming, USA.

Kim, B., and Roque, R. 2006. Evaluation of healing property of asphalt mixtures. Transportation Research Record, Journal of the Transportation Research Board, No. 1790, pp 84-91.

Kringos, N., Schmets, A., and Scarpas, A. 2011. Towards an understanding of the self-healing capacity of asphaltic mixtures. HERON, Vol. 56 (1/2), pp. 45-47.

Little, D.N., Lytton, R.L., Williams, D., and Kim, Y.R. 1999. An analysis of the mechanism of microdamage healing based on the application of micromechanics first principles of fracture and healing. Journal of the Association of Asphalt Paving Technologists, Vol. 68, pp. 501-542.

Little, D.N., Lytton, R.L., Devon, W., and Chen, C.W. 2001. Microdamage healing in asphalt and asphalt concrete, Vol. I: Microdamage and microdamage healing. Project Summary Report. FHWA-RD-98-141, Texas Transportation Institute, The Texas AandM University System, College Station, USA.

Luo, X., Luo, R., and Lytton, L. 2013. Characterization of recovery properties of asphalt mixtures. Journal of Construction and Building Materials, Vol. 48, pp. 610-621.

Maillard, S., de La Roche, C., Hammoum, F., Such, C., and Piau, J-M. 2004. Bitumen healing investigation using a specific fracture test. Journal of Road Materials and Pavement Design, Spec Issue EATA 2004, Vol. 5, pp. 45-63.

Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, F., and Planque, L. 2015. Quantification of biasing effects during fatigue tests on asphalt mixes: non-linearity, self-heating and thixotropy. Journal of Road Materials and Pavement Design, Vol. 16, pp. 73-99.

Moreno-Navarro, F., Sol-Sanchez, M., Rubio-Gamez, M.C. 2015. Exploring the recovery of fatigue damage in bituminous mixtures: the role of healing. Journal of Road Materials and Pavement Design, Vol. 16, pp. 1-15.

Nazzal, M., Kaya, S., and Abu-Qtaish, L. 2012. Evaluation of WMA healing properties using atomic force microscopy. Proc., 7th RILEM International conference on cracking in pavements, Vol.4, RILEM Bookseries, pp. 1125-1134, Delft, Netherlands.

Palvadi, S., Bhasin, A., Motamed, A., and Little, D.N. 2012. Quantifying healing based on viscoelastic continuum damage theory in fine aggregate asphalt specimen. Proc., 7th RILEM International conference on cracking in pavements, Vol.4, RILEM Bookseries, pp. 1115-1123, Delft, The Netherlands.

Phillips, MC. 1998. Multi-step models for fatigue and healing, and binder properties involved in healing. Eurobitume workshop on performance related properties for bituminous, May 3-6, 1998, Luxembourg, No. 115.

Rabe, R. 2008. From loads to roads - the way from truck freight to pavement stress. Proc., Transport Research Area Europe, Apr. 21-24, 2008, Ljubljana.

Santagata, E., Baglieri, O., Dalmazzo, D., and Tsantilis, L. 2009. Rheological and chemical investigation on the damage and healing properties of bituminous binders. Association of Asphalt Paving Technologists, Vol. 78, pp. 567-596.

Santagata, E., Baglieri, O., Tsantilis, L., and Dalmazzo, D. 2013. Evaluation of self healing properties of bituminous binders taking into account steric hardening effects. Journal of Construction and Building Materials, Vol. 41, pp. 60-67.

Sefidmazgi, N.R., Tashman, L., and Bahia, H. 2012. Internal structure characterization of asphlat mixtures for rutting performance using imaging analyses. Journal of Road Materials and Pavement Design, Vol. 13(S1), pp. 21-37.

Shan, L., Tan, Y., and Kim, R. 2013. Establishment of a universal healing evaluation index for asphalt binder. Journal of Construction and Building Materials, Vol. 48, pp. 74-79.

Shen, S., and Carpenter, S. 2007. Dissipated energy concepts for HMA performance: fatigue and healing. Technical report supported by Federal Aviation Administration, University of Illinois, USA.

Shen, S., Chiu, H., and Huang, H. 2009. Fatigue and healing in asphalt binders. CD-ROM. Transportation Research Board Meeting, Washington, DC.

Tan, Y., Shan, L., Kim, Y., and Underwood, B.S. 2012. Healing characteristics of asphalt binder. Journal of Construction and Building Materials, Vol. 27, pp. 570-577.

Van den Bergh, W., and Van der Ven M.F.C. 2012. The influence of ageing on the fatigue and healing properties of bituminous mortars. Proc., SIIIV-5th international congress-sustainability of road infrastructures, Oct. 29-31, 2012, Rome.

Wistuba, M., and Perret, J. 2004. Comparative strain measurement in bituminous layers with the use of ALT. Proc., 2nd international conference on accelerated pavement testing, Sept. 25-29, 2004, Minneapolis, Minnesota, USA.

Wistuba, M., Alisov, A., and Isailović, I. 2013. Ansprache und Steuerung von Healing-Effekten bei Asphalt. Schlussbericht, FE 07.0251/2011/ERB, i. A. des Bundesministeriums für Verkehr, Bau und Stadtentwicklung, Institut für Straßenwesen, Technische Universität Braunschweig.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

E Influence of rest period on asphalt recovery considering nonlinearity and self-heating[5]

Abstract: This paper presents investigation on the asphalt mixture recovery potential using cyclic uniaxial tension-compression test in stress-controlled mode. The recovery potential and its dependence on rest period duration were investigated taking into consideration non-linearity and self-heating effects observed during cyclic loading. In order to preserve the internal specimen's structure a small-size temperature sensor was embedded into asphalt mixture during compaction. It is found, that the effect of nonlinearity on complex modulus recovery is relatively small and that it is not affected by increasing duration of the rest period. The effect of temperature variation in the core of the specimen occurring during cyclic excitation and rest periods has a significant influence on asphalt mixture recovery properties. Self-heating results in a much more rapid recovery of complex modulus than other eventual side effects, such as thixotropy, self-healing and strain relaxation. This effect vanishes when temperature reaches its original value, leaving to the other biasing phenomena dominant in terms of complex modulus recovery.

Keywords: material recovery, nonlinearity, self-heating, rest period.

[5] Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017. Influence of rest period on asphalt recovery considering nonlinearity and self-heating. Published in Journal of Construction and Building Materials, Vol. 140, pp. 321-327, DOI: 10.1016/j.conbuildmat.2017.02.122, Elsevier.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 90 %

E.1 Introduction

Road pavement structures are susceptible to fatigue cracking which initiates in the asphalt material due to repeated heavy traffic loading. The rest periods between each traffic loading repetition may induce the recovery of the material mechanical properties and the partial reversibility of progressive cracking effects. This phenomenon is commonly referred as a self-healing. Such a property can significantly enhance the fatigue life of asphalt pavements and should be taken into considerations during materials selection and pavements design (cf. Di Benedetto et al., 2004; Di Benedetto et al., 2011; Santagata et al., 2013).

In order to address fatigue and self-healing properties of asphalt mixtures, accelerated cyclic laboratory tests are commonly performed. Thereby, damage and self-healing are usually related to the decrease and increase in the complex modulus, respectively. During laboratory cyclic excitation, some biasing effects can appear together with fatigue and self-healing; this is not consistent with field loading conditions (Lundström et al., 2004). Biasing effects such as nonlinearity, self-heating, thixotropy and strain relaxation (for stress controlled tests) can significantly affect the complex modulus evolution and consequently lead to inaccurate fatigue results and erroneous interpretation of the fatigue characteristics (Di Benedetto et al., 2011; Mangiafico et al., 2015). Since all these effects are completely reversible during rest period, they cannot be accounted for self-healing and have to be separately considered. If observed together the term material recovery should be used.

E.2 Objective and research approach

In this work an investigation on the asphalt mixture recovery properties and its rest period duration dependency is performed with the objective of including nonlinearity and self-heating effects in the analysis. For this purpose, uniaxial tension-compression tests on prismatic specimens in stress controlled mode were conducted. Amplitude sweep tests, temperature sweep tests, and discontinuous fatigue tests with single rest periods of different duration (recovery tests) were performed to investigate the evolution of complex modulus. The contribution to the recovery of material properties of effects such as nonlinearity and self-heating together with the combined influence of thixotropy, strain relaxation and self-healing is evaluated and, finally, quantified. Figure E.1 provides the flow chart of the selected research approach.

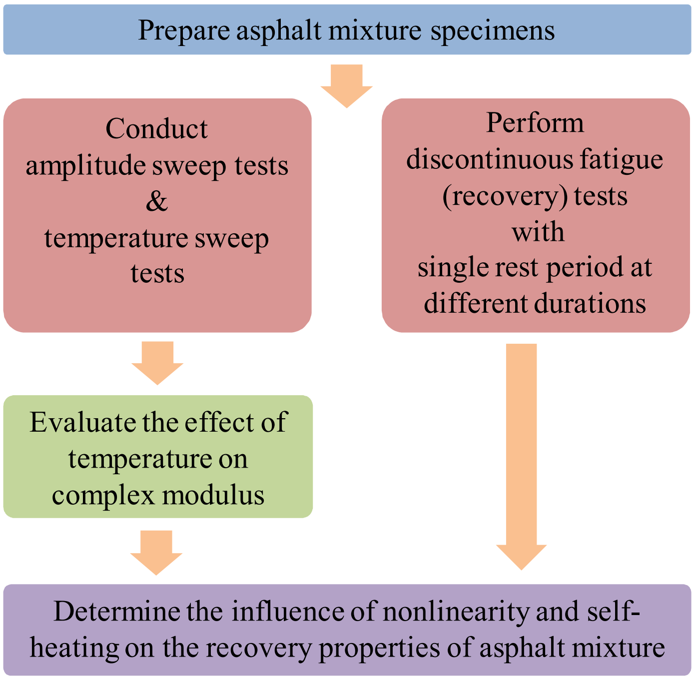

Figure E.1. Flow chart of the selected research approach.

E.3 Experimental study

E.3.1 Material composition and specimen preparation

The investigation of asphalt mixture recovery properties was carried out using a standard asphalt mixture for surface courses, i. e. AC 11 D S. This mixture was prepared with aggregates having maximum grain size of 11 mm and with a bitumen having penetration grade 50/70 (EN 1426, 2013) in percentage of 5.6 % by total mixture weight.

Asphalt mixture was compacted using a segmented steel roller compactor (see Figure E.2), able to produce asphalt mixture slabs (320 × 200 × 50 mm^3) with similar characteristics (air voids distribution, particle distribution, particle orientation and performance properties) compared to those in the field (Renken, 2000).

The compactor uses a steel roller cylindrical sector to induce a kneading action and to apply a downward force to the specimen in both displacement-controlled pre-compaction and stress controlled main compaction phases (Wistuba, 2014). The pre-compaction phase is intended to simulate the compaction effort of the road paver and the main compaction phase is assumed to simulate the compaction by the road roller. Temperature sensors were placed in the loose mixture within the compaction mould and then compaction was performed. Finally, prismatic specimens (50 × 50 × 160 mm^3) were cut from the slabs (see Figure E.2). Further details are presented in the next section.

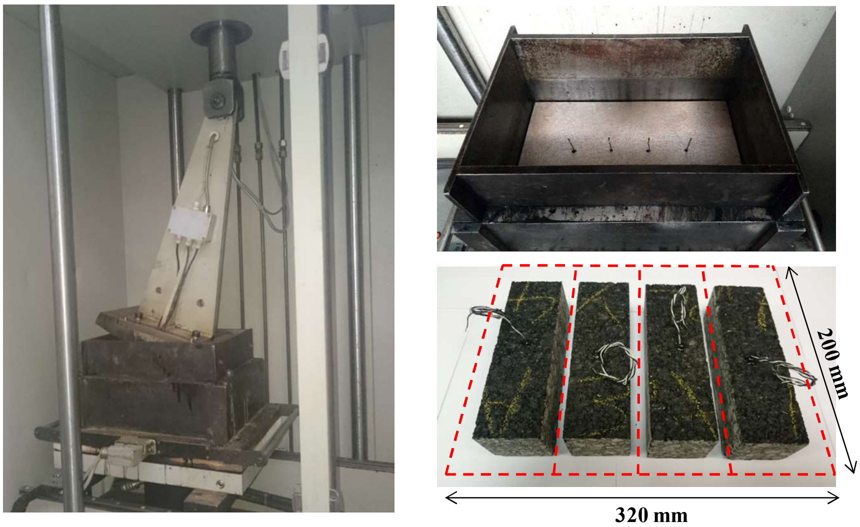

Figure E.2. Segmented steel roller compactor.

E.3.2 Test equipment and procedure

Evaluation of the asphalt mixture recovery properties was performed using uniaxial tension-compression test (UTCT) under stress-controlled mode. This type of test leads to the highest change in material's mechanical properties compared to other stress-controlled fatigue tests (Isailović et al., 2015 a). UTCT provides a satisfactory experimental mean for reliable investigations on the recovery properties of a material, since it induces homogenous stress and strain fields in the test specimen. The test equipment is shown in Figure E.3, left.

In order to monitor the temperature variation inside the specimen during cyclic loading, a temperature sensor PT100 was embedded in the middle part of the sample (see Figure E.3, right). This was done during compaction. The relatively small size of the temperature sensor (5 mm in length and 2 mm in width) and its robustness through ceramic housing, represent two critical advantages of the selected type of internal temperature detectors. These properties guarantee a good integration of the sensors in the asphalt mixture. This is because the temperature probe is directly embedded in the mixture during compaction, limiting potential distortion of the material microstructure. This procedure also avoids the introduction of a (relatively large) point of weakness in the specimen, as it is usually the case, when the sensor is placed after compaction by drilling a hole in the specimen (cf. Mangiafico et al., 2015). Such solution may result in a substantial deviation of the stress field during the tensile phase (Spencer, 1980), due to the binder used to fill the hole's gap between sensor and mixture. The sensor installation proposed in the present research, may significantly limit the distortion of the stress field while providing a consistent continuity of material in the specimen.

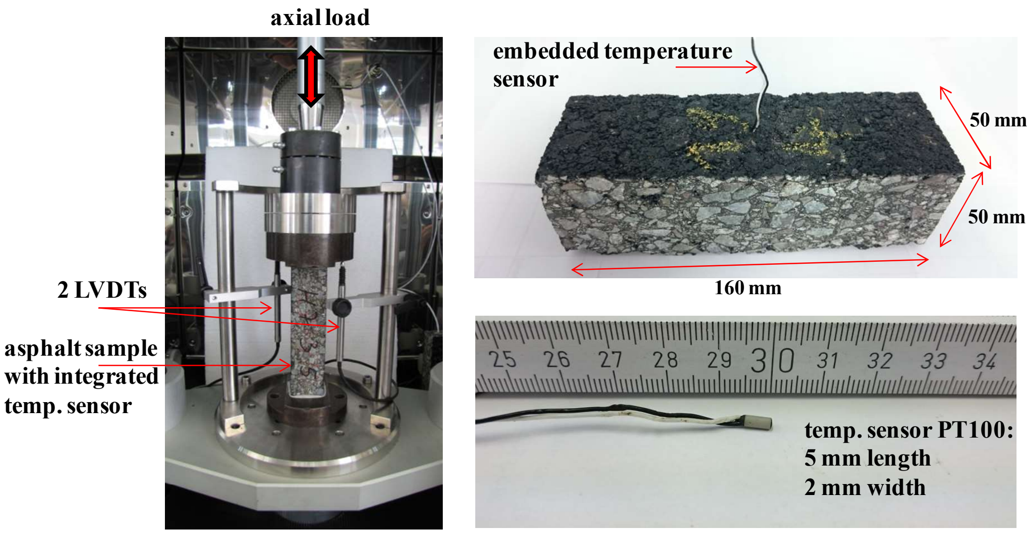

Figure E.3. Test setup (left) and used PT100 temperature sensor (right).

Evaluation of asphalt mixture recovery properties were performed using three types of test modes: (i.) amplitude sweep tests, (ii.) temperature sweep tests, and (iii.) discontinuous fatigue tests with single rest periods of different durations (recovery tests).

All tests were performed in stress-controlled mode in tension and compression at a fixed frequency of 10 Hz. The most important parameters for material analysis, such as stress amplitude, strain amplitude, temperature, etc., were monitored and recorded during the entire test duration.

In order to obtain the viscoelastic properties and the complex modulus-temperature dependence of the selected asphalt mixture, amplitude sweep tests at different temperatures were performed. This was done with the purpose of quantifying the influence of temperature variation within the asphalt sample during cyclic loading on the complex modulus evolution. This type of test was designed with a stepwise increase of the stress amplitude from 0.3 MPa to 1.9 MPa, with increment of 0.1 MPa. In total, 17 loading sequences were applied each consisting of 50 cycles. This number of loading cycles was sufficient in order to achieve the specified stress amplitude. Three test repetitions were performed at each temperature: 15, 17.5, 20, 22.5 and 25 °C.

Taking into consideration that the progressive loading applied during amplitude sweep tests can generate a certain degree of damage, the viscoelastic properties measured in the progress of the loading sequence (steps) could be underestimated, which would lead to erroneous results. This can be proved by conducting one loading sequence with selected stress amplitude at the observed temperature. In order to cover the temperature range from the amplitude sweep tests, one loading sequence (50 cycles) with specific stress amplitude is applied to the sample at the following temperatures: 15, 17.5, 20, 22.5 and 25 °C. The test starts at 15 °C and ends at 25 °C, with 7200 seconds of conditioning time between each temperature. A single stress amplitude of 0.7 MPa is applied; this stress level is also used for the discontinuous fatigue tests (recovery tests). The stress amplitude of 0.7 MPa was selected in pre-testing procedure in order to achieve fatigue life between 80000 and 100000 loading cycles for discontinuous fatigue test.

In order to provide better assessment and to determine the influence of the rest period duration on the recovery properties, discontinuous fatigue tests with single rest period were conducted. The rest period was introduced when the asphalt experienced sufficient damage after the initial loading phase, in which the stiffness reduction is highly influenced by non-linearity, heating and thixotropy, as clearly indicated by (Di Benedetto et al., 2004). After reaching 64 % of the initial complex modulus, the rest period was applied, leaving the specimen in a stress free condition (cf. Isailović et al., 2016). After the rest period, the specimen was loaded by a new loading sequence till failure (Figure E.4, loading phase 2).

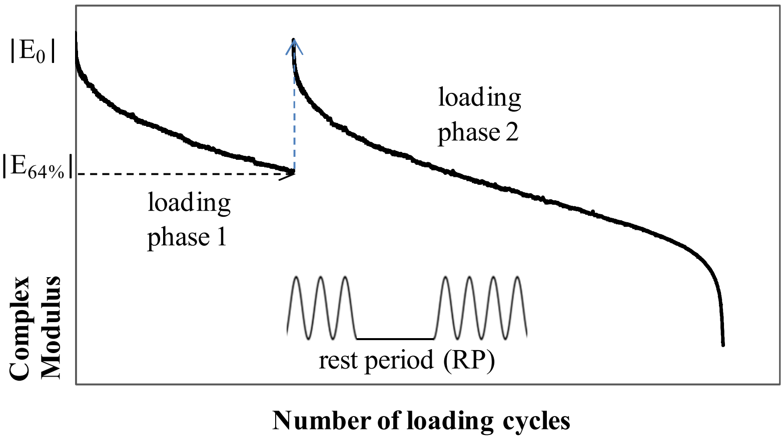

Figure E.4. Test protocol for discontinuous fatigue test: loading phase 1 + rest period (RP) + loading phase 2 (schematic).

The recovery tests were performed at a stress amplitude of 0.7 MPa and at a temperature of 20 °C. Several rest period durations were imposed, from 500 up to the 86400 seconds, with three test replicates. This is because it was expected to observe an increase in recovery potential for longer rest periods (Carpenter and Shen, 2006; Palvadi et al., 2012; Isailović et al., 2015 b).

E.4 Experimental results

E.4.1 Amplitude sweep tests

The stress level in amplitude sweep tests was stepwise increased from 0.3 MPa to 1.9 MPa, with 50 loading cycles in each sequence (step). The corresponding absolute value of complex modulus for each loading step was calculated as the mean value from cycles 40 to 50. This was done since the specified stress amplitude in each loading sequence was achieved after 30 to 40 loading cycles.

Figure E.5 shows an evolution of the complex modulus (mean value) over the different imposed stress levels for an amplitude sweep test conducted at 20 °C. The complex modulus experiences a continuous decrease, meaning that no linear viscoelastic behaviour can be observed for the specific loading conditions. Similar results were obtained at other test temperatures.

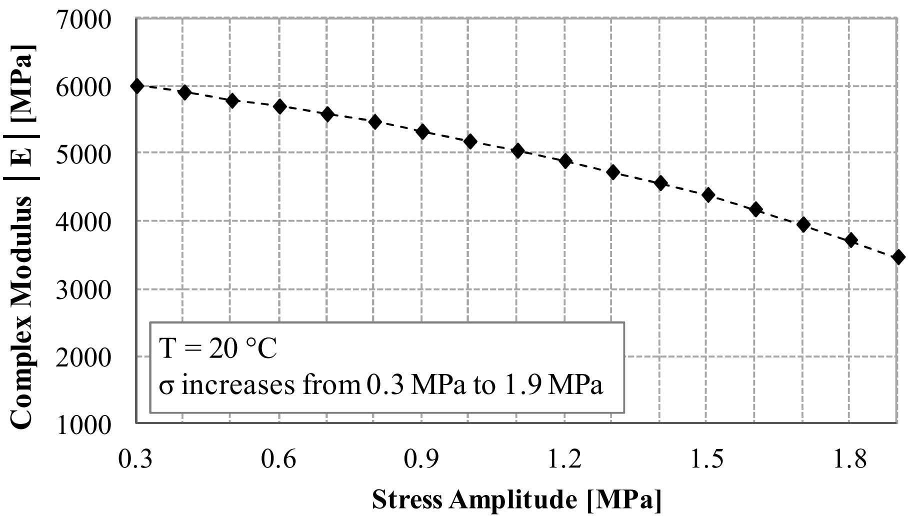

Figure E.5. Evolution of the absolute value of complex modulus over the various stress levels in amplitude sweep test at 20 °C.

In order to obtain the temperature - complex modulus dependence for the considered stress amplitudes, the results from all test repetitions at five temperatures were taken into consideration. Figure E.6 summarizes the results for different stress levels and testing temperatures. It can be noticed that the evolution of the complex modulus obtained at the same stress amplitude over the considered temperature range shows a linear trend for all applied stress amplitudes. This was also observed earlier by Di Benedetto et al. (2011) at small strain amplitudes in strain-controlled mode. The linear regression lines do not exhibit parallel offset with increased stress amplitude, indicating coupled effects of viscoelastic properties and loading history.

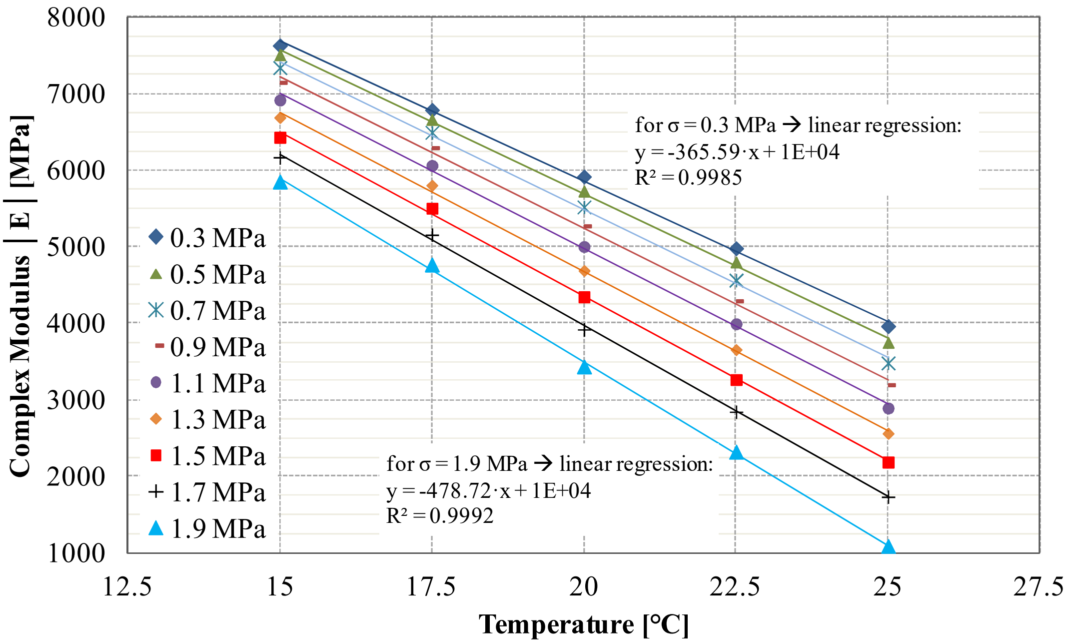

Figure E.6. Evolution of the absolute value of complex modulus in function of temperature at various stress amplitudes in amplitude sweep test.

E.4.2 Temperature sweep tests

The results obtained from amplitude sweep tests were verified using temperature sweep tests at a stress amplitude of 0.7 MPa. This was done with the purpose of avoiding the effect of loading history and conducting just one loading sequence with 50 cycles at each considered temperature. As mentioned previously, again the absolute value of complex modulus was calculated as a mean value from cycles 40 to 50.

Figure E.7 shows the results from both amplitude and temperature sweep tests. It can be seen that both test types show quite similar complex modulus-temperature dependencies at the same stress amplitude. This implies that the loading history in amplitude sweep test until 0.7 MPa stress amplitude does not affect the overall asphalt mixture viscoelastic properties and no damage was induced. From both linear regressions a relative change of the absolute value of complex modulus per one degree temperature decrease, or increase respectively, can be determined i. e.

- 397.12 MPa/1 °C for amplitude sweep test and
- 385.88 MPa/1 °C for temperature sweep test.

Based on these values, a mean value of complex modulus variation over temperature for 0.7 MPa stress amplitude was calculated, resulting in 391.5 MPa/1 °C. This value was subsequently used for the quantitative estimation of the self-heating effect on complex modulus evolution in recovery tests at a stress amplitude of 0.7 MPa and at a temperature of 20 °C.

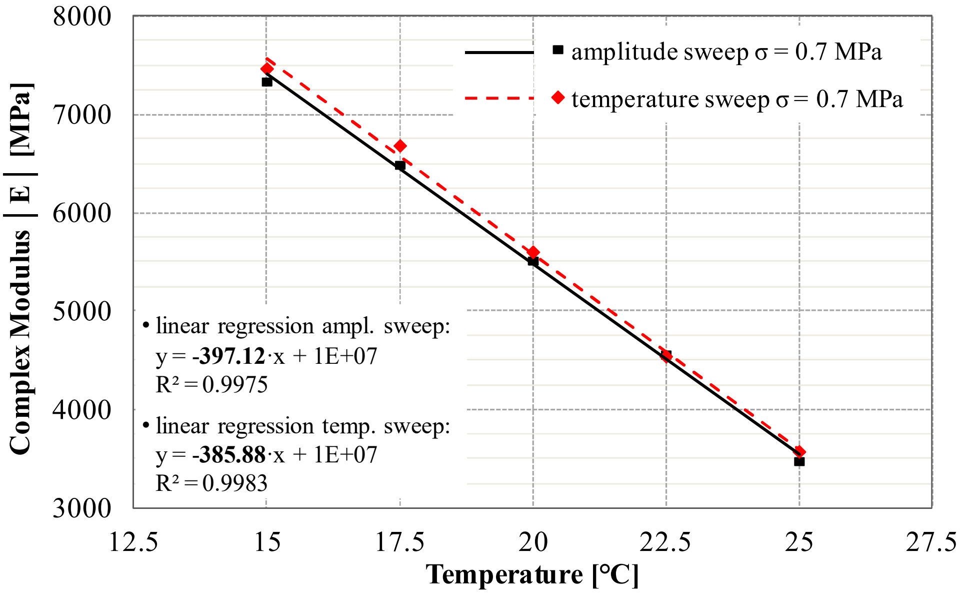

Figure E.7. Evolution of the absolute value of complex modulus in function of temperature at the stress amplitude of 0.7 MPa in amplitude and temperature sweep tests.

E.4.3 Recovery tests

In order to estimate asphalt mixture recovery properties, discontinuous fatigue tests with one rest period at a temperature of 20 °C and at a stress amplitude of 0.7 MPa were conducted. Several rest period durations were imposed, from 500 up to the 86400 seconds, with three test repetitions.

Figure E.8 shows the evolution of the complex modulus in one recovery test with a rest period of 86400 seconds. The complex modulus recovery is calculated as the difference between values at the beginning of the loading phase 2 (first cycle) and the end of the loading phase 1 (last cycle). A relatively high recovery of the complex modulus is stated during the rest period and it is almost at the same level compared to the beginning of the first loading phase (see Figure E.8). It must be remarked that the second loading phase was extended until failure occurred. However, the development of the macro-crack was not experienced across the placement point of the temperature sensor, confirming the good experimental practice followed from preparation of the asphalt mixture specimens. However, these results cannot be compared with other research works (Di Benedetto et al., 2011; Mangiafico et al., 2015) where only partial fatigue tests were performed without reaching the fatigue strength limit.

Considering the recovery of the complex modulus at different rest period durations it can be seen that increased recovery time leads to more distinct complex modulus increase (Figure E.9). The complex modulus recovery during a 24 h rest period (86400 s) can reach up to 2380 MPa (see Figures E.8 and E.9), which is more than 35 % of the initial complex modulus. This value cannot be attributed to self-healing phenomena only.

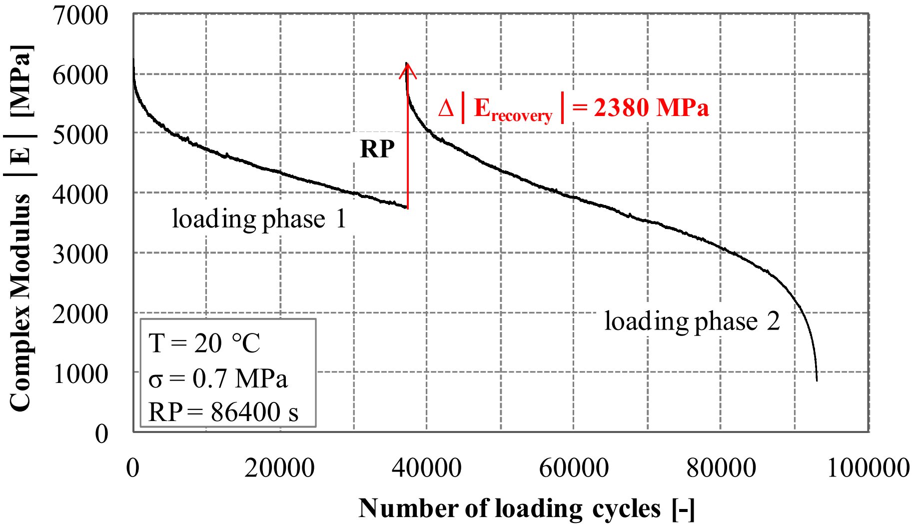

Figure E.8. Evolution of the absolute value of complex modulus in function of the number of loading cycles in the recovery test with a rest period of 86400 seconds.

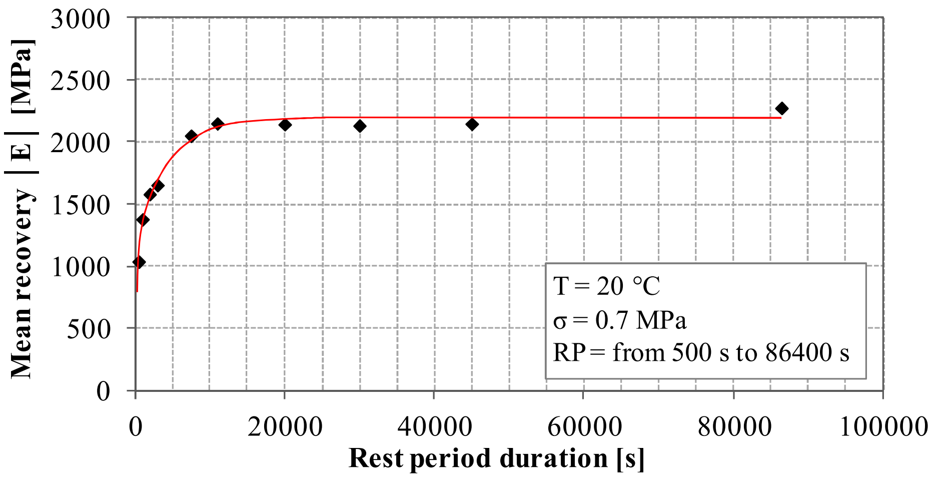

Figure E.9. Mean recovery of the absolute value of complex modulus (from three test repetitions) for different rest period durations.

E.4.4 Influence of biasing effects on complex modulus recovery

By inducing a rest period in the quasi-stationary complex modulus phase, it can be assumed that asphalt mixture has already experienced damage to a certain degree and, beside nonlinearity, self-heating, thixotropy and strain relaxation, self-healing also contributes to the overall complex modulus recovery.

The nonlinearity effect is observed at the beginning of the cyclic loading and disappears when a specified stress amplitude is achieved. Figure E.10 shows a magnified representation of Figure E.8, where a rest period of 86400 seconds was imposed. It can be seen that the stress amplitude of 0.7 MPa cannot be achieved immediately, while it increases progressively until loading cycle number 31. By considering the non-linear viscoelastic asphalt properties (cf. Figure E.5), the increase in stress amplitude within the first 30 cycles provokes a decrease in complex modulus, that can be addressed to the nonlinearity. The influence of other effects in this initial phase is assumed to be negligible (cf. Di Benedetto et al., 2011). Therefore, the nonlinearity effect $\Delta|E_{nonlinearity}|$ can be calculated as the difference between the first value of complex modulus $|E_2|_{beg}$ in the loading phase 2 and the complex modulus $|E_2|_{0.7MPa}$ at cycle 31, where the stress amplitude of 0.7 MPa was achieved, reading

$$\Delta|E_{nonlinearity}| = |E_2|_{beg} - |E_2|_{0.7MPa} = 6146.7 - 5974.7 = 172 \quad [\text{MPa}] \tag{E.1}$$

For this specific test, 172 MPa out of total 2380 MPa were recovered as a consequence of material nonlinearity.

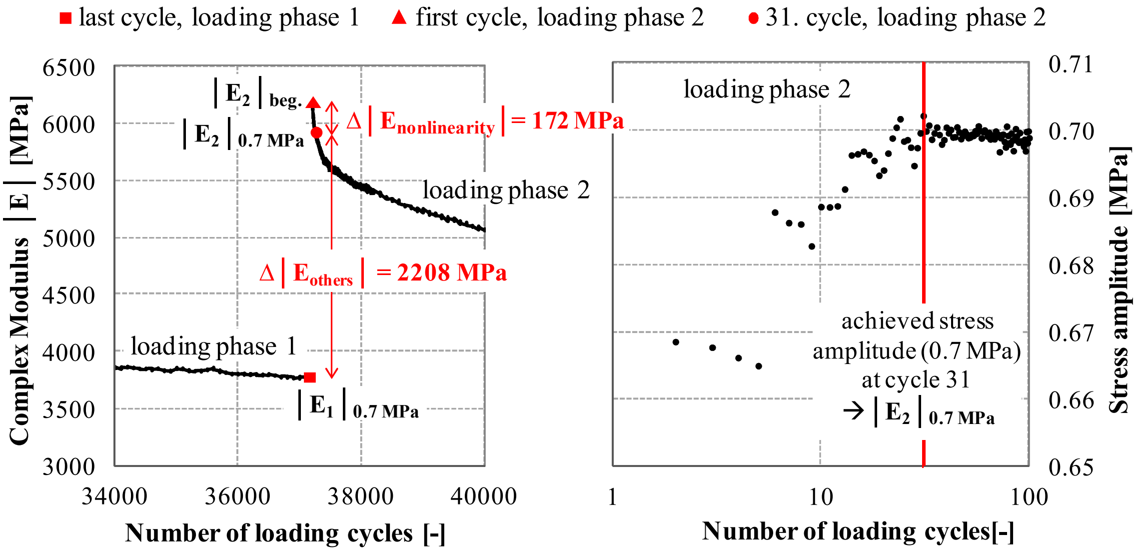

Figure E.10. Calculation procedure for nonlinearity effects: close look representation of complex modulus and stress amplitude evolution in recovery test with rest period duration of 86400 seconds.

By calculating the effects of nonlinearity on complex modulus recovery for all rest period durations considered (see Figure E.11), it can be seen that the nonlinearity effect is not affected by increased recovery time. The value for nonlinearity recovery remains approximately on the same level for various rest period durations.

The influence of self-heating on the complex modulus recovery was determined based on the temperature evolution recorded through an embedded sensor in the core of the specimen (see Section E 3.2). Figure E.12 shows the variation of the specimen temperature in one recovery test with a rest period of 86400 seconds.

A significant temperature increase, which is caused by the dissipated viscous energy (Di Benedetto et al., 2011), can be observed in the first loading phase. Based on stress-free conditions during the rest period, the temperature is continuously reduced down to the initial value imposed at the beginning of the test (equal to thermal chamber temperature). In the subsequent loading sequence (loading phase 2) a temperature increase is observed again, with dramatic evolution up to failure (see Figure E.12). This is due to the increased strain amplitude which is linked to high energy dissipation, and thus, a consistent increase in temperature. The observed trend is opposite to what was found in tests performed under strain-controlled mode, where thermal temperature equilibrium occurred and temperature reached a plateau stage (cf. Lundström et al., 2004; Mangiafico et al., 2015).

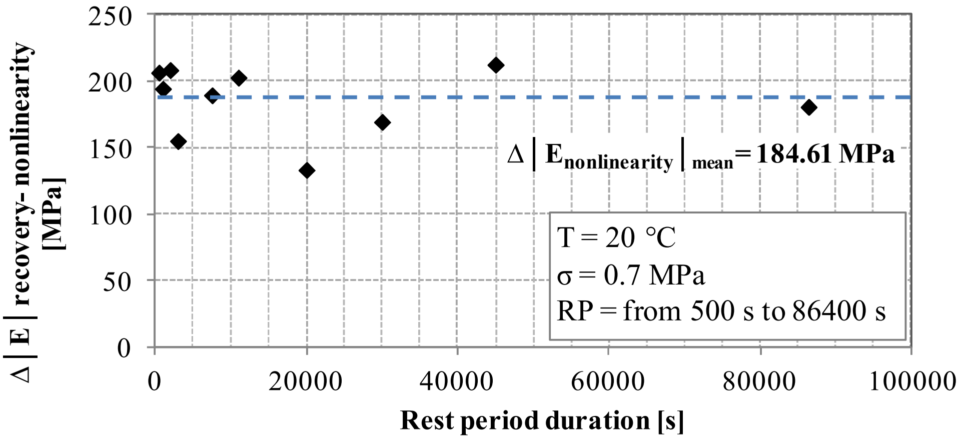

Figure E.11. Mean recovery of the absolute value of complex modulus (from three test repetitions) as a consequence of the nonlinearity effect over various rest period durations.

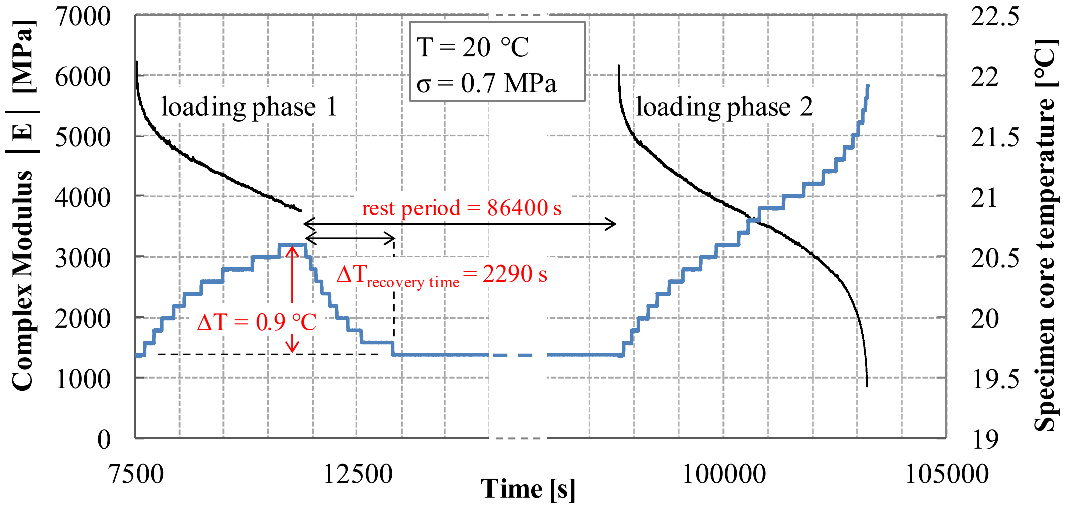

Figure E.12. Time evolutions of absolute values of complex modulus and specimen core temperatures in recovery test with a rest period of 86400 s.

Considering asphalt mixture temperature dependency, the temperature decrease of 0.9 °C, experienced during the rest period (see Figure E.12) results in increased complex modulus. Using the value of complex modulus change over temperature of 391.5 MPa/1 °C (see Section E.3.2) the influence of self-heating on complex modulus recovery can be calculated as follows:

$$\Delta \left| E_{\text{self-heating}} \right| = 0.9\ °C \cdot 391.5 \text{MPa}/1\ °C = 355.05 \quad [\text{MPa}] \tag{E.2}$$

Based on Equations E.1 and E.2, it can be seen that the influence of self-heating effect on complex modulus recovery is double compared to the effect of nonlinearity. This counts for the long rest period durations, where temperature is recovered completely. If the rest period is not long enough, a partial temperature recovery leads to lower complex modulus recovery (see Figure E.13). Based on recovery tests, and considering various rest period durations, it was possible to determine the actual rest period duration beyond which the self-heating effect does not further affect the complex modulus recovery. For the specific asphalt mixture and test parameters used in this research the plateau value is obtained after 2500 seconds approximately.

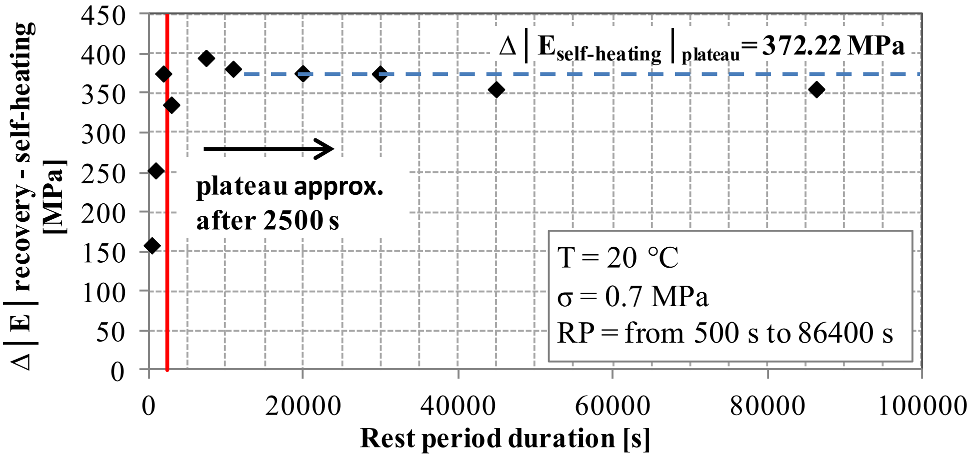

Figure E.13. Mean recovery of absolute value of complex modulus (from three test repetitions) as a consequence of self-heating effect over various rest period durations.

By subtracting the effects of nonlinearity and self-heating from the overall recovery it is possible to calculate the influence of further effects which drive the complex modulus recovery, and to estimate their rest period duration sensitivity. Clear separation of effects such as thixotropy, self-healing and strain relaxation has not been successfully achieved at this stage of research; therefore, they are considered as a single portion. Figure E.14 shows that the complex modulus recovery governed by these effects is highly dependent on rest period duration.

Considering the mean value of the complex modulus recovery for nonlinearity (184.61 MPa, Figure E.11), and the mean values for self-heating (372.22 MPa, Figure E.13), thixotropy, self-healing and strain relaxation (1623.12 MPa, Figure E.14) in the quasi-stationary (plateau) phase, it can be stated that the effects of thixotropy, self-healing and strain relaxation have the largest influence on the complex modulus recovery, which is 74.4 %. The effects of self-heating are estimated to 17.1 %, and nonlinearity to 8.5 %, which have significantly lower influence compared to the other effects. However, they must not be neglected.

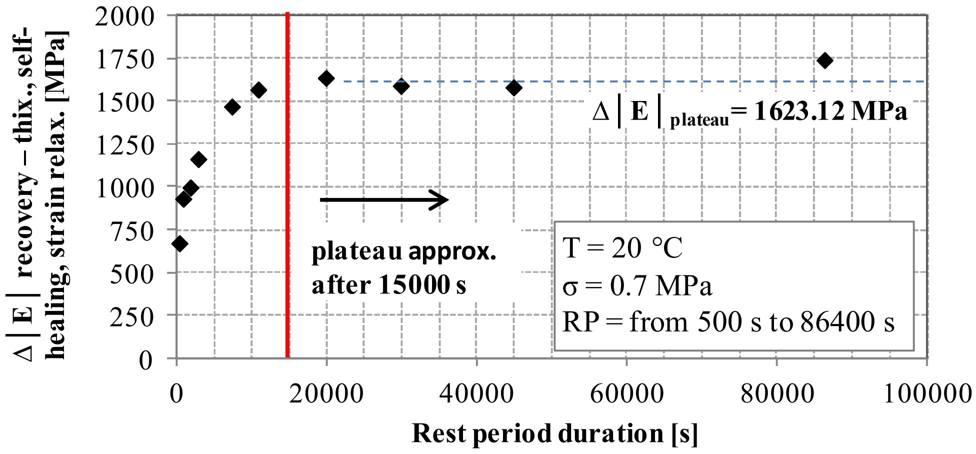

Figure E.14. Mean recovery of the absolute value of complex modulus (from three test repetitions) as a consequence of thixotropy, self-healing and strain relaxation effects over various rest period durations.

In order to investigate the impact on recovery rate of the effects investigated, the percentage contribution to the complex modulus recovery was calculated for each of them. The effect of nonlinearity was not taken into consideration, because of its rest period duration independency.

The results are plotted in Figure E.15. It can be seen that for short rest period durations the effect of self-heating contributes more rapidly to complex modulus recovery. This effect vanishes after fully recovery of temperature (at 2500 seconds), where the effect of thixotropy, self-healing and strain relaxation solely contribute to complex modulus recovery.

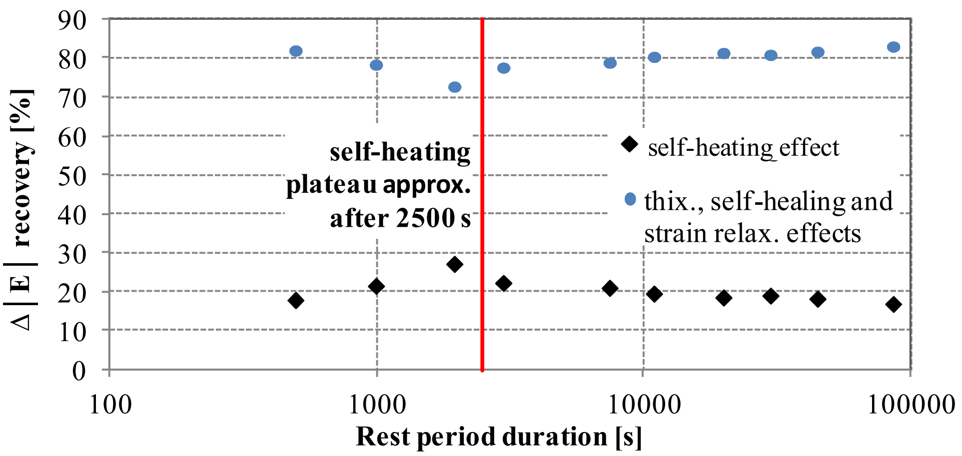

Figure E.15. Percentage recovery of the complex modulus as a consequence of self-heating, thixotropy, self-healing and strain relaxation effects (without nonlinearity effect).

E.5 Summary and conclusions

In this study, the recovery potential of a hot mix asphalt mixture was investigated in detail, using cyclic uniaxial stress controlled tension-compression tests. The rest period duration dependency was studied taking into consideration nonlinearity and self-heating effects observed during cyclic loading. Three types of test modes were applied: (i) amplitude sweep tests, (ii) temperature sweep tests, and (iii) discontinuous fatigue tests with single rest periods of different durations (recovery tests).

In order to examine the influence of self-heating on recovery properties, a temperature sensor was embedded in the asphalt mix sample during compaction. In such a way an efficient sensor integration can be achieved, providing a consistent continuity of the material within the specimen, and limiting distortion of the stress field.

Based on comprehensive test evaluation, the following conclusions can be drawn:

- The effect of nonlinearity on the complex modulus recovery is not affected by increased rest period durations, and is relatively low (8.5 %) compared to the other effects such as self-heating, thixotropy, self-healing and strain relaxation.
- The effect of temperature variation in the core of the specimen, occurring during cyclic excitation and during rest periods (self-heating), on complex modulus recovery is highly affected by the rest period duration and can account up to 17.1 % of the overall complex modulus recovery.
- For short rest period durations, the effect of self-heating contributes more rapidly to complex modulus recovery than other biasing effects, such as thixotropy, self-healing and strain relaxation. This effect vanishes when temperature reaches its original value (after 2500 seconds in this experiment), leaving to other biasing phenomena dominant in term of complex modulus recovery.

These findings are based on investigations of one asphalt mixture type only, and may be different for others. More research on this field is needed in order to examine recovery phenomena of mechanical properties more in detail by separating the effects of thixotropy, self-healing and strain relaxation during cyclic loading. For further investigations the presented procedure for core temperature measurement is highly recommended, since no development of macro-cracks was observed across the placement point of the temperature sensor. This confirms the soundness of the experimental practice followed during the preparation of asphalt mixture specimens.

E.6 References

Carpenter, S., and Shen, S. 2006. A dissipated energy approach to study HMA healing in fatigue. Transportation Research Record, Journal of the Transportation Research Board, No 1970, pp. 178-185.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundström, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Di Benedetto, H., Nguyen, Q-T., and Sauzéat, C. 2011. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 12(1), pp. 129-158.

EN 1426. 2013. Bitumen and bituminous binders - Determination of needle penetration. European Standard.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 a. Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests. Proc., 8th International RILEM SIB symposium, Vol. 11, RILEM Bookseries, pp. 693-709, 7-9 October, 2015, Ancona, Italy.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 b. Asphalt recovery properties in fatigue test with single rest period. Proc., 6th international conference - bituminous mixtures and pavements, Jun. 10-12, 2015, Thessaloniki, Greece.

Isailović, I., Wistuba, M, and Cannone Falchetto, A. 2016. Assessment of healing properties of asphalt mixtures. Proc., 8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements, Vol. 13, RILEM Bookseries, pp. 253-258, Jun. 7-9, 2016, Nantes, France.

Lundström, R., Ekblad, J., and Isacsson, U. 2004. Influence of hysteretic heating on asphalt fatigue characterization. Journal of Testing and Evaluation, Vol. 32 (6), pp. 484-493.

Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, F., and Planque, L. 2015. Quantification of biasing effects during fatigue tests on asphalt mixes: non-linearity, self-heating and thixotropy. Journal of Road Materials and Pavement Design, Volume 16, pp. 73-99.

Palvadi, S., Bhasin, A., Motamed, A., and Little N.D. 2012. Quantifying healing based on viscoelastic continuum damage theory in fine aggregate asphalt specimen. Proc., 7th Rilem international conference on cracking in pavements. Vol. 4, RILEM Bookseries, pp 1115-1123, Jun. 20-22, 2012, Delft, The Netherlands.

Renken, P. 2000. Influence of specimen preparation onto the mechanical behaviour of asphalt aggregate mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, pp. 729-735, Sept. 20-22, 2000, Barcelona, Spain.

Santagata, E., Baglieri, O., Tsantilis, L., and Dalmazzo, D. 2013. Evaluation of self healing properties of bituminous binders taking into account steric hardening effects. Journal of Construction and Building Materials, Vol. 41, pp. 60-67.

Spencer, A.J.M. 1980. Continuum Mechanics (Dover Books on Physics), Dover, New York, USA.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

F Fatigue investigation on asphalt mixture layers' interface[6]

Abstract: In this paper, the interface shear fatigue performance is investigated based on a new fatigue test protocol, which includes both cyclic shear and normal static compressive load. Several asphalt structure types are tested at five temperatures (from -10 °C to 50 °C) and three normal stress levels (from 0 to 0.50 MPa). Based on fatigue tests at three different shear amplitude levels unique fatigue functions of the layers' interface were identified. It was found that the interface shear fatigue performance is highly dependent on normal stress state and increases with increasing normal stress. This is a direct consequence of the enhanced friction, adhesion and interlock at the shear interface. Observing the fatigue lives at different test temperatures, the best resistance was observed at lowest temperature. From a practical viewpoint, it is highly recommended to perform the test without normal stress application, since this can better reflect the research and practice experience, while keeping the testing protocol to a reasonable level of complexity.

Keywords: layers' interface, direct shear test, fatigue, normal load.

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[6] Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2017. Fatigue investigation on asphalt mixture layers' interface. Published in Journal of Road Materials and Pavement Design, Vol. 18, sup4, pp. 514-534, DOI: 10.1080/14680629.2017.1389087, Taylor and Francis.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 90 %

F.1 Introduction

Asphalt pavement consists of several layers which are built subsequently. In order to ensure a good and durable bond between them, the surface of the existing layer is usually cleaned and covered with a thin layer of an asphaltic tack coat material.

The function of the layer bond is to efficiently transfer the shear stresses at the layers' interface, which are due to braking, accelerating and turning wheel phenomena, and to the simple action of rolling wheel loads (Romanoschi and Metcalf, 2001). The bond is achieved by the interaction of adhesion, friction and interlock effects at the layers' boundary, where the exact contribution of each of them is temperature, mixture and tack coat source and application rate dependent (Wistuba et al., 2016).

The performance of the road structure is directly influenced by the bond conditions between pavement layers (Tozzo et al., 2014). Pavement with full bonding among all asphalt layers can act as a whole structural unit. A poor or missing bond results in a serious change of the three-dimensional stress state in the entire structure and will lead to significant increase in tension stresses at the bottom of the asphalt layers (Wistuba et al., 2016). Consequently, an essential reduction of the structural bearing capacity and thus a much shorter service life is expected. This was clearly showed by Weber (1991), where the deflections of two beams with and without bond were compared. Based on linear elastic bending theory, a nine-fold increase in the deflection of a three-layer beam (without bond) was observed.

Several monotonic shear test methods were developed over the years (Raab and Partl, 2004; Santagata and Canestrari, 1994; Sholar et al., 2004; West et al., 2005; Woods, 2004). In order to simulate the real field conditions, cyclic shear tests were also proposed (Carr, 2001; Crispino et al., 1997; Diakhate et al., 2011; Donovan et al., 2000; Gorszczyk and Malicki, 2012; Romanoschi and Metcalf, 2001; Sanders, 2001; Tozzo et al., 2014; Wellner and Ascher, 2007; Wheat, 2007; Zofka et al., 2015); however, they only focused on specific conditions or parameters, such as temperature effects or compressive normal load, without considering the influence of both parameters on shear fatigue phenomenon. Each of these shear tests is generally suitable for the evaluation of the interface shear properties, but so far no test method has been internationally established and widely accepted. The variety of testing procedures and test conditions leads to a lack of result repeatability making a direct comparison across the different methods very complex. In extreme cases, the test results are contradictory.

The current German procedure for evaluation of the interface shear properties is based on a simplified monotonic shear test, Leutner test (FGSV, 2012). This test consists of applying a constant shear displacement rate across the layers' interface, where shear strength is obtained at the peak shearing force. In spite of its simplicity and short test procedure, this type of test is not able to simulate real traffic load conditions. This is because the imposed shear stress is not cyclic and does not include the application of a normal force to the specimen. The actual interface behaviour is unknown and the test results cannot be appropriately used in the mechanistic pavement design.

F.2 Objective and research approach

Because of the obvious disadvantages of the monotonic shear test (Leutner test) used in Germany, and its inability to obtain the viscoelastic and fatigue properties at the layers' interface, there is a need to introduce a new test procedure. This procedure should be able to apply different cyclic shear stress conditions coupled to a normal stress, which simulates the vertical traffic load. This is especially important for mechanistic pavement design, because the actual procedure does not consider the change in mechanical properties of the layer' interface during the service life.

This paper presents the research results from a research project devoted to fatigue investigation of asphalt mixture layers' interface (Wistuba et al., 2016); as a basis, the testing device developed by Wellner and Ascher (2007) was used. It represents a cyclic version of the Leutner shear test with the possibility of applying a static normal load, which simulates the vertical load of the vehicles' axles.

The main objective of this work was to clarify if the existing test apparatus can be employed for the fatigue evaluation of the layers' interface and, if so, which test parameters should be used. Over 400 specimens were prepared in order to determine the influence of various asphalt mixtures, tack coats, test temperatures and compressive normal stresses on fatigue behaviour of the layers' interface. For each material combination, amplitude sweep tests were performed in order to determine conditions and initial parameters for fatigue tests and the limits of the linear viscoelastic domain. Following, fatigue tests were conducted at three stress states with the goal of obtaining the bond fatigue functions. Figure F.1 provides the flow chart of the selected research approach.

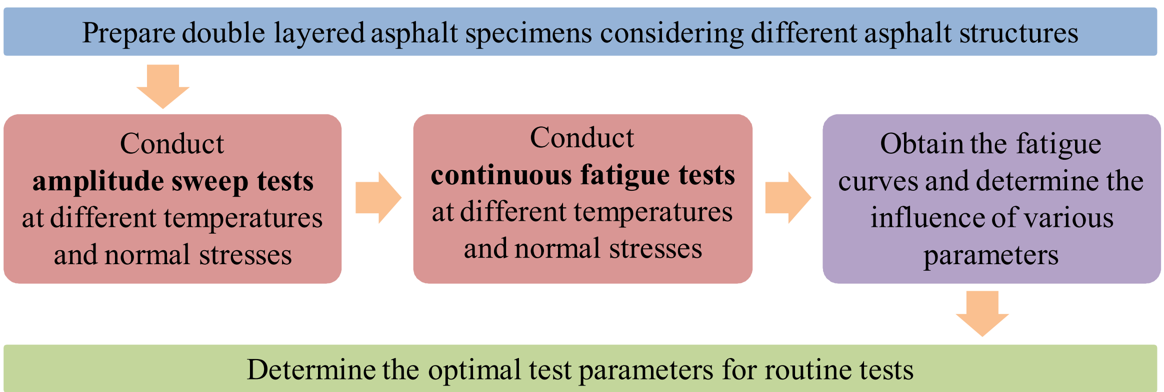

Figure F.1. Flow chart of the selected research approach.

F.3 Experimental study

F.3.1 Materials and specimens' preparation

The interface shear fatigue performance was evaluated on double-layer specimens of asphalt mixture. Three asphalt mixtures were considered: stone mix asphalt SMA 11 for surface course, asphalt concrete AC 16 B S for binder course and asphalt concrete AC 22 T S for base course. Different asphalt binders (plain and polymer modified) and aggregate types were used. Table F.1 shows the composition of each asphalt mixture.

Table F.1: Composition of the asphalt mixtures investigated

Characteristic		Unit	Asphalt mixture type		
			AC 22 T S	**AC 16 B S**	**SMA 11 S**
Grain size distribution	≤ 0.063 mm	M.-%	5	7.1	10
	0.063 - 0.125 mm	M.-%	1.2	1.9	1.8
	0.125 - 0.25 mm	M.-%	2.7	2.6	2.2
	0.25 - 1 mm	M.-%	11.4	11.3	7.9
	1 - 2 mm	M.-%	8.2	7.4	5.3
	2 - 5.6 mm	M.-%	12.2	14.2	15.7
	5.6 - 8 mm	M.-%	15.2	12.1	12.2
	8 - 11.2 mm	M.-%	14.3	19	40.6
	11.2 - 16 mm	M.-%	18.8	21.6	4.3
	16 - 22.4 mm	M.-%	9.9	2.8	-
	22.4 - 31.5 mm	M.-%	1.1	-	-
	sum	M.-%	100	100	100
Aggregate type		-	limestone	basalt	basalt
RAP addition		M.-%	30	-	-
Binder type		-	50/70	25/55-55 A	25/55-55 A
Binder content		M.-%	4.1	4.7	6.0
Bulk density		g/cm³	2.374	2.475	2.461
Air voids content		V.-%	7.4	6.5	3.9

For the compaction of the asphalt mixture, a segment steel roller compactor, known as German Sector Compactor, was used; a set of 500 × 700 mm^2 double-layer slabs were compacted in three steps using the following compaction procedure (FGSV, 2007): (i) compaction of the lower slab layer, (ii) application of the tack coat on the next day and (iii) compaction of the upper slab layer after breaking process of tack coat occurred (ca. 3 hours after tack coat application). After cooling, cylindrical samples having diameter ϕ = 99 mm were cored. Figure F.2 shows the coring scheme (left) and a double-layer sample (right), which was subjected to fatigue loading.

In this study, three types of the tack coat were used:

- cationic polymer modified emulsion **C60**BP1-S with 60 mass-% of asphalt binder content,
- cationic emulsion **C40**BF1-S with 40 mass-% of asphalt binder content,
- cationic emulsion C60B1-S (**U60K**) with 60 mass-% of asphalt binder content.

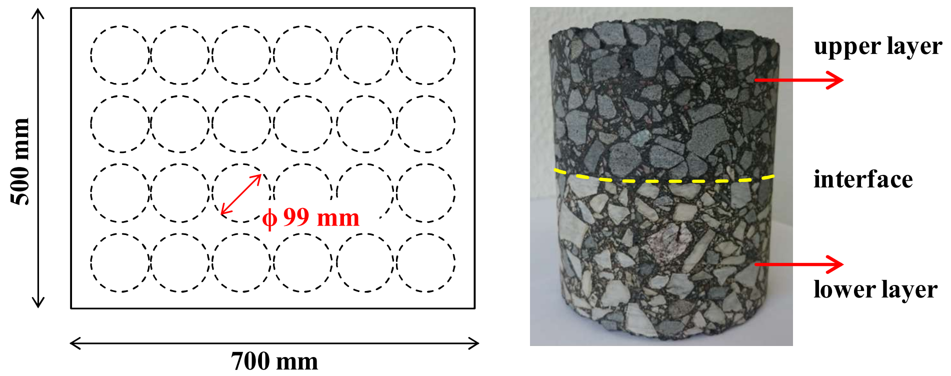

Figure F.2. Coring scheme for slabs (500 × 700 mm^2) compacted with roller steel compactor (left) and a double-layer sample (SMA 11 on AC 16 B S) (right).

Based on various asphalt mixtures and emulsions, five different interface bonds were considered in total. Table F.2 gives an overview of the applied layer-bond combination and their composition.

Table F.2: Layer-bond combinations and composition

Bond type	Emulsion type	Application rate of emulsion [g/m²]	Layers	Height of asphalt layers [cm]
A	C60BP1-S	300	AC 16 B S on AC 22 T S	5 cm on 6 cm
B	C40BF1-S			
C	C60BP1-S	200	SMA 11 S on AC 16 B S	4 cm on 5 cm
D	C40BF1-S			
E	C60B1-S	300	AC 22 T S on AC 22 T S	6 cm on 6 cm

F.3.2 Test equipment

Cyclic shear tests were used to investigate the interface shear fatigue properties. In order to obtain a satisfactory and precise allocation of the sample inside the testing frame, the double-layer cylindrical specimen was glued within four-steel half-shells and stored for at least 24 hours at room temperature for complete curing (see Figure F.3). The gap width that is exposed to direct shear stress was set to 1 mm (Wellner and Ascher, 2007).

In order to induce cyclic loading at the interface between the two asphalt mixture layers, the test frame was installed in a servo-hydraulic machine equipped with a 25 kN load cell. A continuous cyclic loading was imposed in displacement control to induce damage at the layers' interface. The testing frame is presented in Figure F.4. The sinusoidal cyclic shear load was applied at a single fixed frequency of 10 Hz. For the application of the accurate cyclic shear displacement, two vertical strain gauges were attached at both sides of the testing frame. In order to simulate a real field stress conditions, in addition to the cyclic shear load, a compressive normal stress can be applied. This normal stress is static, because dynamic application would lead to a higher complexity of the test frame. In order to monitor and control the potential axial (horizontal) displacement through high normal stress application, a third, horizontally placed strain gage was employed (see Figure F.4). Prior to testing, the specimen was conditioned for 2 hours at the desired testing temperature.

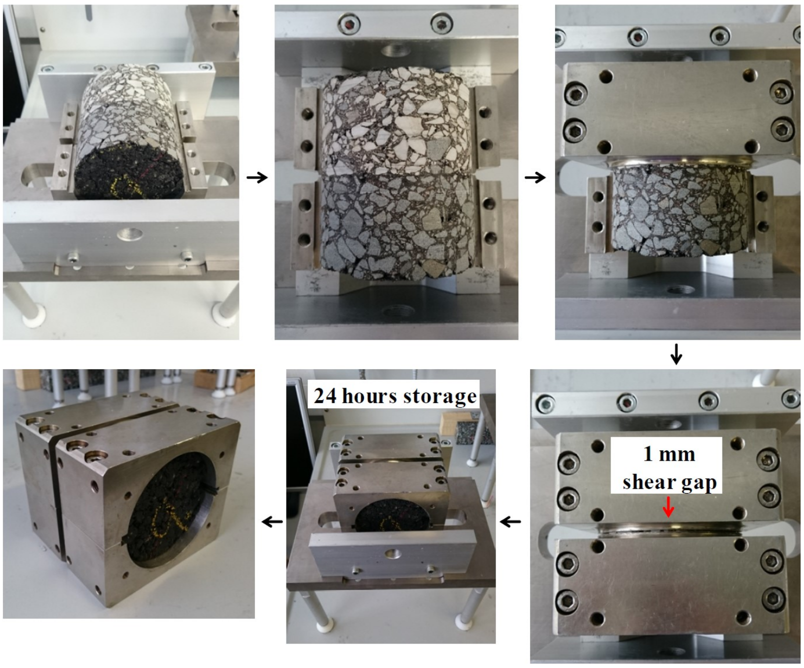

Figure F.3. Specimen preparation for the cyclic shear test.

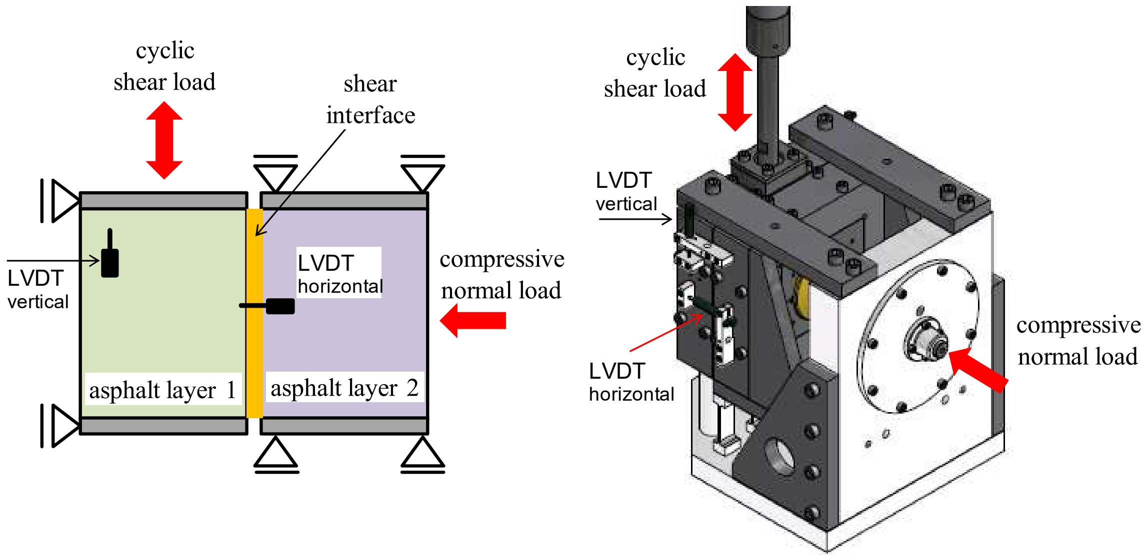

Figure F.4. Schematic representation of the cyclic shear apparatus.

During the tests, displacement and force were recorded with a data acquisition system and the shear stress (τ_n) was calculated as follows (Wellner and Ascher, 2007):

$$\tau_n = \frac{F_n}{A_{eff}} \quad \text{[MPa]}, \tag{F.1}$$

where: F_n = force amplitude at cycle n [N], and A_{ff} = interface area [mm^2].

The interface shear stiffness ($K_{s,n}$) was defined as the ratio between shear stress and relative displacement at the interface (Equation F.2, Wellner and Ascher, 2007):

$$K_{s,n} = \frac{\tau_n}{U_n} \quad \text{[N/mm}^3\text{]}, \tag{F.2}$$

where: τ_n = shear stress at cycle n [MPa], U_n = displacement amplitude at cycle n [mm].

F.3.3 Testing procedure

Since no previous work was performed on fatigue tests with the shear apparatus presented in this study (see above), the shear displacement amplitudes were chosen through a pre-testing procedure using an amplitude sweep test. Within this test it is also possible to determine the linear viscoelastic domain of the asphalt mixture interface.

This type of test was designed with a stepwise increase of the shear displacement amplitude from 0.008 to 0.2 mm. In total, 25 loading sequences were applied, each consisting of 200 cycles. The number of loading cycles was sufficient to achieve the specified displacement amplitude. The proposed protocol is shown in Figure F.5. For each material and test condition, at least two sweep tests were performed.

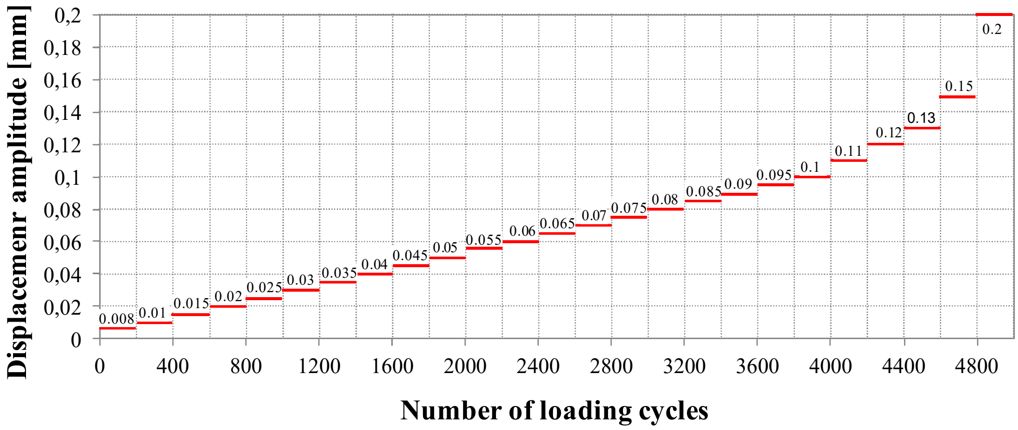

Figure F.5. Test protocol for the amplitude sweep test: 25 load steps, each with 200 loading cycles.

Based on amplitude sweep test results, continuous fatigue tests were conducted at three displacement amplitudes with three test replicates for each material and test condition, with the goal of obtaining shear fatigue functions for the interface bond. For each type of layer-bond combination (A-E in Table F.2) three normal stresses and at least three test temperatures were considered in order to find appropriate test parameters (Table F.3), for a total of 47 combinations. Based on the stress calculations conducted by Wellner and Ascher (2007), the normal stress at the point of maximal shear stress (the edge of the tire) does not exceed 0.50 MPa. Therefore, this value will be used as a maximum in shear fatigue evaluation (see Table F.3).

Table F.3: Test matrix for fatigue testing of asphalt layer interface (grey combinations were considered)

Bond type	Normal stress [MPa]			Temperature [°C]				
	0	0.25	0.50	-10	10	20	30	50
A	yes	yes	yes	yes	yes	yes	yes	yes
B	yes	yes	yes	no	yes	yes	yes	no
C	yes	yes	yes	no	yes	yes	yes	no
D	yes	yes	yes	no	yes	yes	yes	no
E	yes	yes	yes	no	yes	yes	yes	no

F.4 Experimental results

F.4.1 Amplitude sweep tests

In order to determine the input parameter for the fatigue tests, amplitude sweeps were performed. As previously indicated, the displacement level in amplitude sweep tests was stepwise increased from 0.008 to 0.2 mm.

Figure F.6 shows one example of amplitude sweep test conducted on bond type E at 20 °C and 0 MPa normal stress. Increasing displacement amplitudes lead to lower interface shear stiffness. However, the nominal force required for achieving a specific displacement amplitude increases up to a maximum limit value (0.04 mm shear amplitude, vertical dashed line). After that point, a significant reduction of force is observed. Although the displacement amplitude further increases, the force remains at a low level due to the failure of the layers' interface. The remaining force is associated only to the friction between the asphalt layers. Similar evolutions were obtained for other bond types and other temperatures.

Each shear amplitude at which a disproportionate sudden drop in force amplitude occurs, can be considered as a limit for shear fatigue tests (black dashed line in Figure F.6), since this would imply a very short fatigue life. The maximum displacement (shear) amplitude for fatigue tests should be selected in correspondence of two displacement steps below than the specifically identified threshold (see the right end arrow on the top of Figure F.6).

Preliminary tests have shown that the lowest shear amplitude that can be applied by the testing machine used in this research is 0.008 mm. It represents the lower amplitude limit for the present shear fatigue tests. Based on amplitude sweep test in Figure F.6 and statements made above, the following displacement amplitudes for fatigue tests can be recommended for bond type E: 0.01, 0.02 and 0.03 mm.

By applying the highest value of the normal stress (0.50 MPa), an initial increase in force with increased displacement amplitude can be also observed (see Figure F.7). After reaching the maximum value, the force amplitude does not fall, showing a quasi-stationary evolution. This is a direct consequence of the increased normal stress which induces higher friction between the asphalt layers. On this basis, it is quite difficult to define the displacement amplitude at which layers' interface exhibits failure.

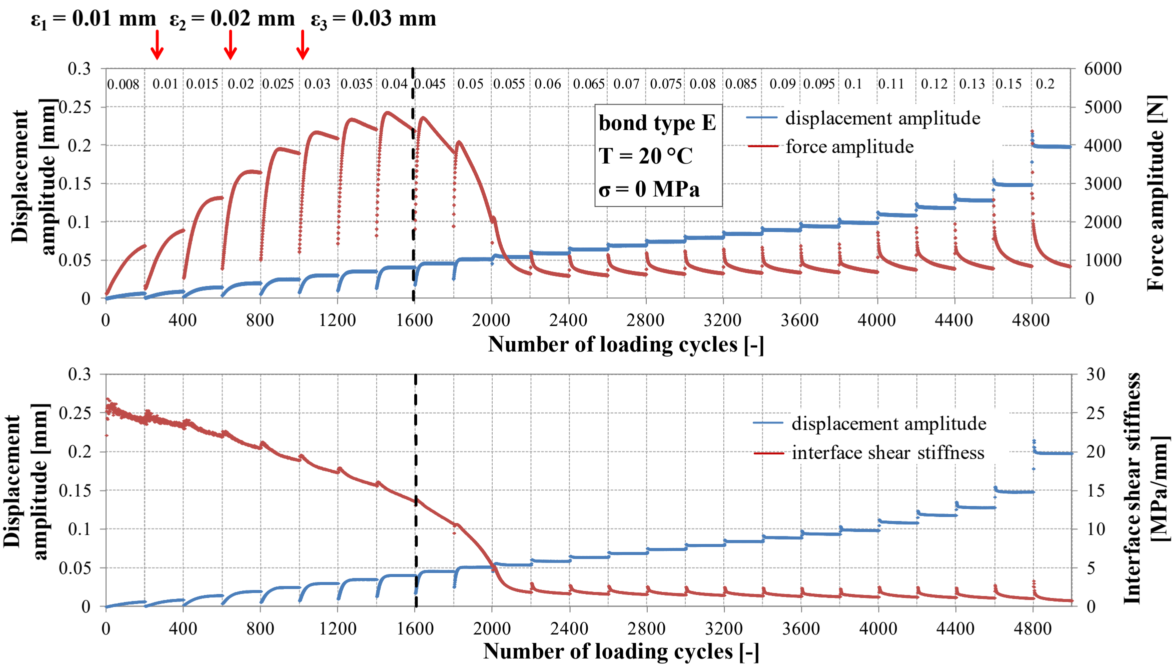

Figure F.6. Evolution of the displacement amplitude, interface shear stiffness and force amplitude in amplitude sweep test conducted on bond type E at 20 °C and 0 MPa normal stress.

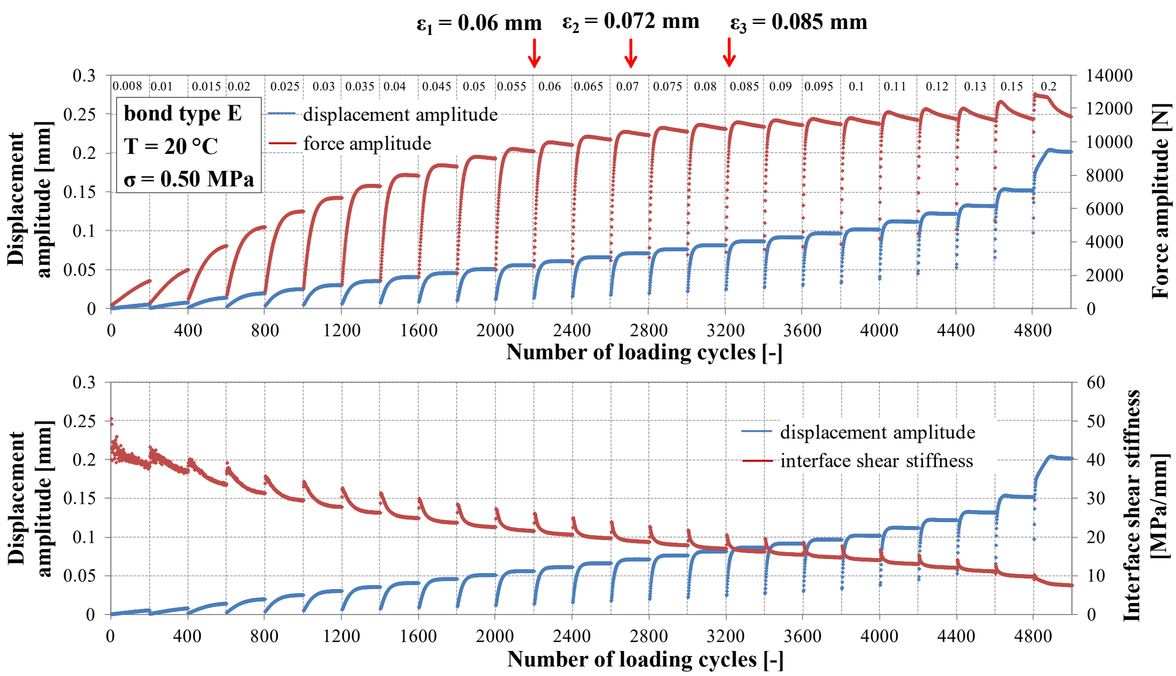

Figure F.7. Evolution of the displacement amplitude, interface shear stiffness and force amplitude in amplitude sweep test conducted on bond type E at 20 °C and 0.50 MPa normal stress.

In order to determine the linear viscoelastic domain of the layers' interfaces at different temperatures and normal stress states, the corresponding value of interface shear stiffness for each loading step was calculated as the mean value from cycles 190 to 200. Figure F.8 shows an evolution of the interface shear stiffness (mean value) over the different imposed displacement levels for an amplitude sweep test conducted at bond type C at 20 °C and at three normal stresses (0, 0.25 and 0.50 MPa). It means that no linear viscoelastic behaviour can be observed for the specific loading conditions. Similar results were obtained at other test temperatures.

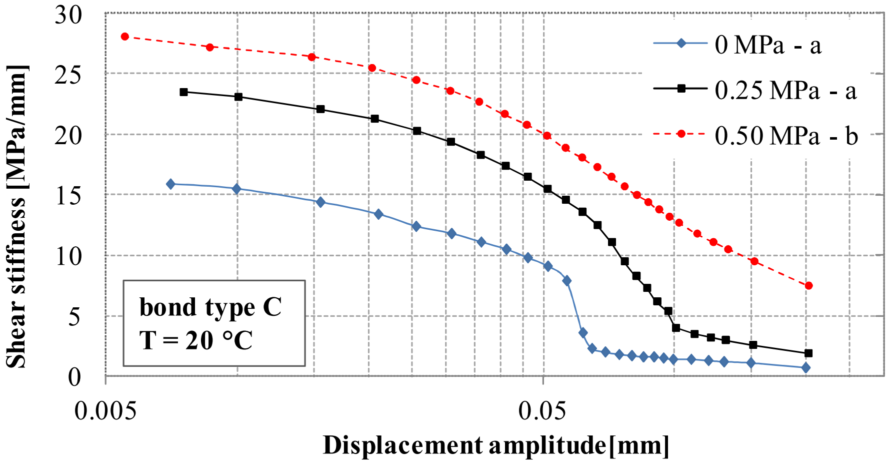

Figure F.8. Bond type C: evolution of the interface shear stiffness over the displacement amplitudes for amplitude sweep tests at 20 °C and three normal stress levels (0, 0.25 and 0.50 MPa).

F.4.2 Fatigue tests

F.4.2.1 Material behaviour - cyclic shear loading

For the evaluation of the material behaviour during the cyclic shear test, the following material parameters were considered: interface shear stiffness, phase angle and dissipated energy. Figures F.9 and F.10 show the evolution of these three parameters in several shear fatigue tests at various temperatures and normal stress levels.

Interface shear stiffness decreases gradually with increased number of loading repetitions as a consequence of the bond deterioration at the interface. This was also examined in the work of Diakhate et al. (2011), where a double shear test was used. Two typical evolutions of the shear stiffness can be observed, depending on the magnitude of the normal stress (Figures F.9 and F.10).

For the tests without normal stress, similarly to the conventional fatigue tests (Di Benedetto et al., 2004) three phases of the stiffness decay can be recognized:

- a rapid decrease of shear stiffness at the beginning of the test,
- a quasi-stationary phase of the shear stiffness decay, and
- propagation phase, where bond failure occurs.

After the propagation phase, the interface shear stiffness remains at a very low level. This is mainly attributed to the friction within layers' interface, where the effects of adhesion and interlock are relatively low. This bond behaviour is also observed at 10 °C and 0.25 MPa, most likely because of the increased brittleness of the layers' interface compared to 20 °C.

With higher normal stress levels, shear stiffness does not exhibit three-stage evolution, since no rapid failure of the layers' interface occurs (see Figure F.9). This is a direct consequence of the applied normal stress, which through its confining action makes the effects of friction, adhesion and interlock much more effective. In this case, the shear stiffness shows a trend for which, the higher the normal stress is, the higher the interface shear stiffness at failure is (see Figure F.9, top). This shear stiffness evolution was also observed at 30 °C without normal stress. This is because the layers' interface at this temperature shows a more viscous behaviour than at 20 °C or 10 °C. The potential evolution of the shear stiffness was recognized at 10 °C and 0.50 MPa normal stress as well.

Due to the different bond viscosity, the interface shows increasing shear stiffness values for decreasing test temperatures (Figure F.10). This was also observed for increased normal stress levels at the same displacement amplitudes (see Figure F.8).

As a result of continuous cyclic excitation of the layers' interface in fatigue shear test, the phase angle presents a constant increase which is highly dependent on the level of normal stress and temperature (see Figures F.9 and F.10). After the bond failure (at constant shear stiffness), the phase angle remains fairly constant. The highest values were detected in tests without normal stress and at higher temperatures. Rarely, a decrease in phase angle during the shear fatigue test was observed (e.g. for bond type B).

Dissipated energy (W_n) for each loading cycle was calculated as follows:

$$W_n = \pi \cdot F_n \cdot U_n \cdot sin\varphi_n \qquad \text{[Nmm]}, \tag{F.3}$$

where: F_n is the force amplitude at cycle n [N], U_n is the displacement amplitude at cycle n [mm] and ϕ_n is the phase angle at cycle n.

As a consequence of the constant material deterioration in displacement controlled fatigue test, the dissipated energy should decrease with increased number of loading cycles (because of the stress amplitude reduction). Figures F.9 and F.10 show the evolutions of the dissipated energy in direct shear fatigue test at different normal stress levels and at different test temperatures. Both an initial decrease and increase of the dissipated energy can be observed. One possible reason for the increased energy dissipation is the higher increase in phase angle, which cannot be compensated by the stress amplitude reduction.

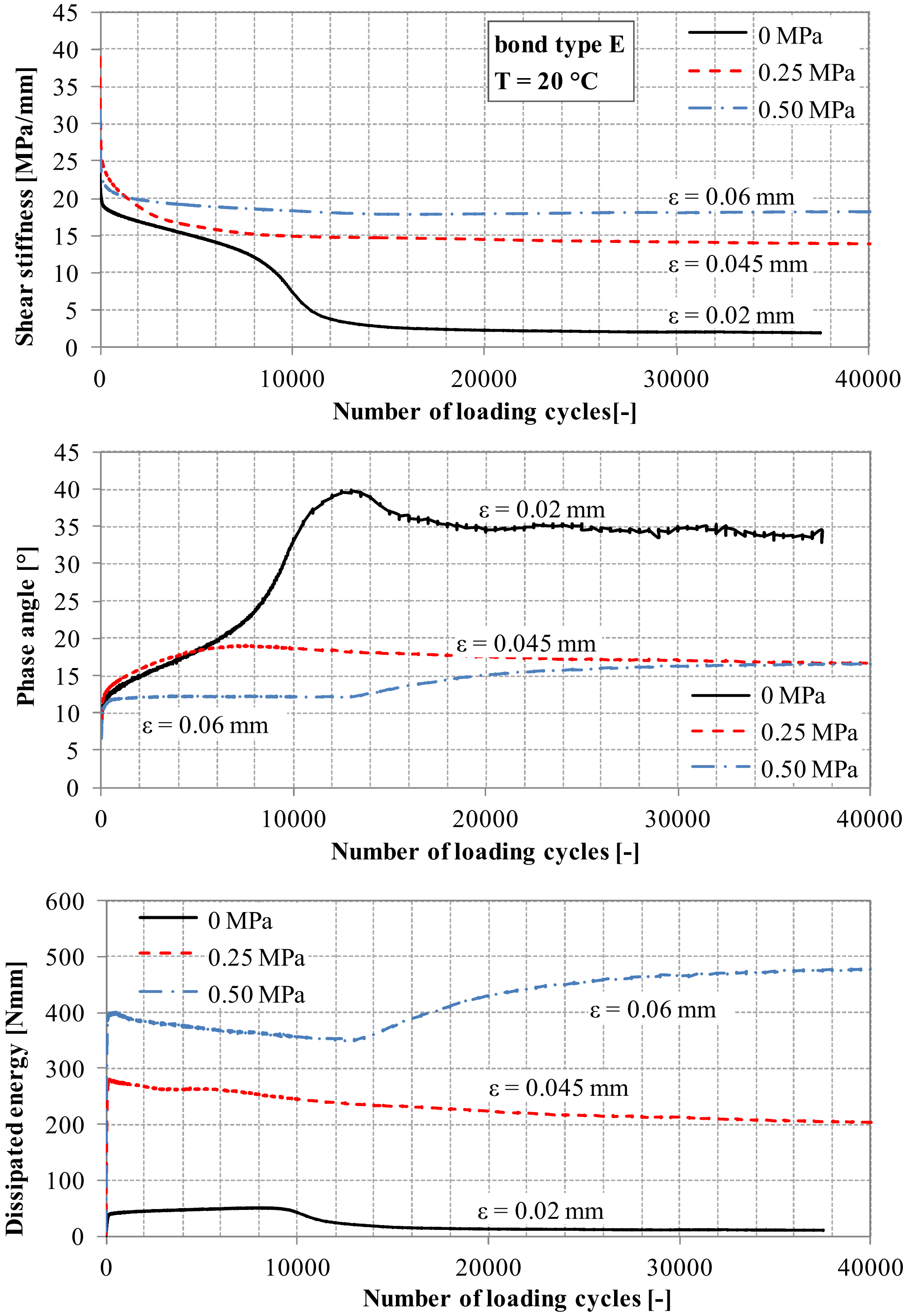

Figure F.9. Bond type E: evolution of the interface shear stiffness, phase angle and dissipated energy over the number of loading cycles for fatigue tests at 20 °C and three normal stress levels (0, 0.25 and 0.50 MPa).

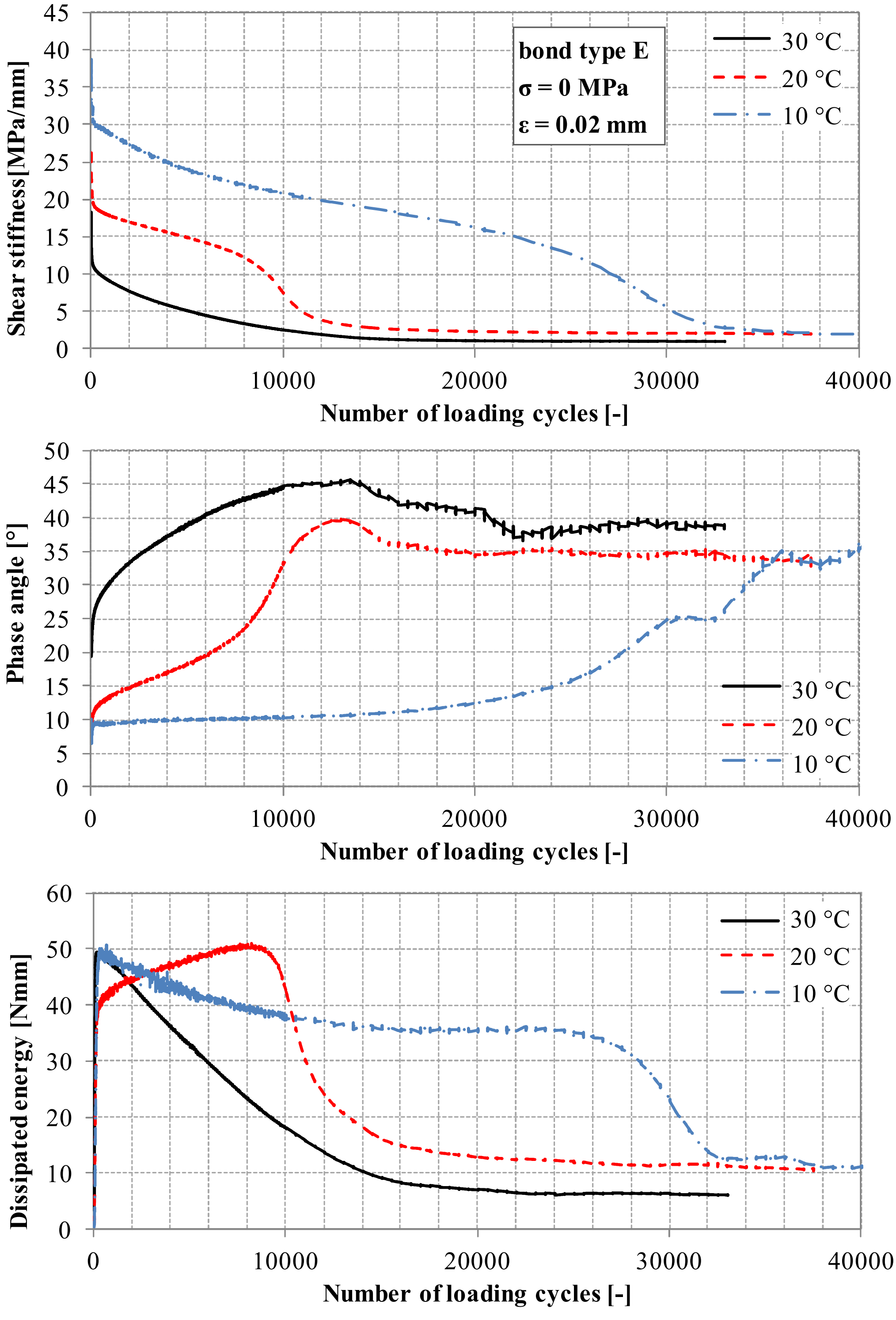

Figure F.10. Bond type E: evolution of the interface shear stiffness, phase angle and dissipated energy over the number of loading cycles for fatigue tests at normal stress 0 MPa and three test temperatures (30, 20 and 10 °C).

F.4.2.2 Failure criteria for direct shear test

In order to obtain the correlation between number of loading cycles at failure and applied displacement amplitude, several failure criteria were considered.

Based on research results, energy-related criteria (Hopman et al., 1989; Rowe and Bouldin, 2000) are not applicable for the determination of the fatigue correlated number of loading cycle, because of the non-uniform energy dissipation during the fatigue tests (see previous section). The use of this type of criteria could lead to non-consistent research results and erroneous evaluation.

Referring to fatigue tests performed on asphalt mixtures, a conventional failure criterion was also investigated (Di Benedetto et al., 2004). This is related to the number of loading cycles at failure (N_{50}), where 50 % decrease in interface shear stiffness occurs. Figure F.11 shows an example of the interface shear stiffness evolution at different normal stresses.

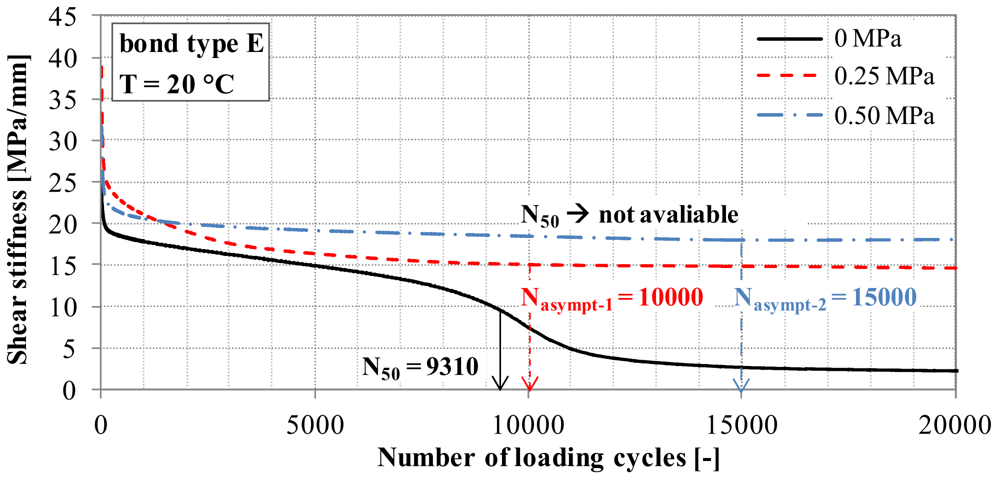

Figure F.11. Bond type E: evolution of the interface shear stiffness, over the number of loading cycles for fatigue tests at 20 °C and three normal stress levels (0, 0.25 and 0.50 MPa).

As can be seen, 50 % decrease of the initial stiffness can be achieved only for a test without normal stress application. For the tests with 0.25 and 0.50 MPa normal stress, interface shear stiffness shows a potential evolution which ends at a relatively high level. Therefore, there is a need to find appropriate fatigue criterion and determine the numbers of loading cycles at failure for tests performed under normal stress conditions. Taking into consideration that in these tests interface shear stiffness settles at a relatively stable constant level for very high number of loading cycles, fatigue can be characterized as a point where shear stiffness reaches its asymptotic value (N_{asympt}, Figure F.11). It is assumed that interface bond in this phase is completely destroyed, where the residual shear stiffness is a consequence of the increased friction at the layers' interface. Based on this, conventional failure criterion (N_{50}) was used for tests without normal stress and asymptotic failure criterion (N_{asympt}) for tests with normal stress.

F.4.2.3 Displacement amplitude dependency

As described in Section F.3.3, for each bond type (A-E) and normal stress and temperature variation, fatigue tests at three displacement amplitudes and with three test replicates were conducted. The results from at least nine tests are fitted and presented in form of a power function (fatigue curve):

$$U = C_1 \cdot N_{50/asympt}^{C_2} \qquad \text{[mm]}, \tag{F.4}$$

where: where U is the displacement amplitude [mm], $N_{50/\text{asympt}}$ is the number of loading cycles at failure [-] and C_1, C_2 are function parameters [-].

Figure F.12 shows one resulting shear fatigue function for bond type E at 20 °C and 0 MPa normal stress. As can be seen, increasing displacement amplitudes lead to a shorter fatigue life of the layers' interface.

For some bond types beside the threefold test repetitions, no sufficiently good regressions were achieved because of the high result scattering. This was mainly observed for tests at 10 °C, independently on the applied normal stress. One example is represented by bond type B at 10 °C and 0 MPa normal stress, where no relationship between displacement amplitude and fatigue life could be obtained. This is probably due to an interaction of lower temperature, rough layer's surface (binder course on base course), low binder content of the bituminous emulsion (40 %) and production-related inconstancy that makes the interface bond more susceptible to uncontrolled failure.

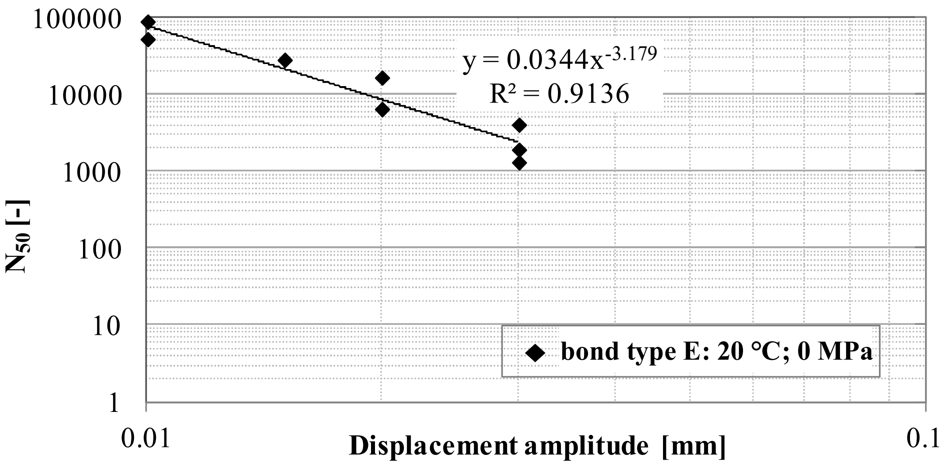

Figure F.12. Bond type E: displacement amplitude over the number of loading cycles at failure at 20 °C and 0 MPa normal stress.

Beside high scatters obtained for some bond types at specific test conditions, over 80 % of the entire set of power functions (35 in total) has determination coefficient R^2 higher than 0.7 (see Table F.4). Only two fatigue functions had determination coefficient lower than 0.5.

Table F.4: Percentage distribution of the determination coefficient of fatigue functions for all shear fatigue tests

Determination coefficient R^2 [-]	Percentage distribution [%]
< 0.50	5.71
$0.50 \leq R^2 < 0.70$	13.33
$0.70 \leq R^2 < 1.0$	80.95

F.4.2.4 Normal stress dependency

As shown in Section F 4.2.1, the evolution of the interface shear stiffness is highly dependent on the level of applied normal stress. Figure F.13 presents two sides of the layers' interface after shear fatigue test at 20 °C without and with 0.50 MPa compressive normal stress. It is visually clear that a higher normal stress is associated to a larger portion broken aggregates at layers' interface (bright regions, Figure F.13). This is a direct consequence of the relatively high normal stress application and enhanced friction, adhesion and interlock at the shear interface.

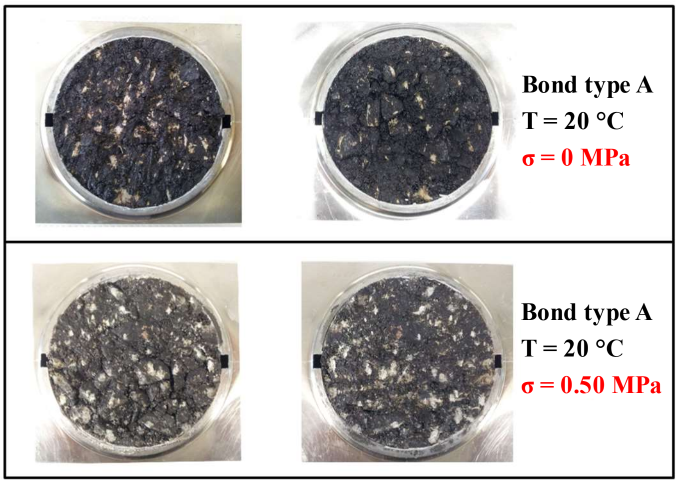

Figure F.13. Bond type A: two sides of the layers' interface after shear fatigue test at 20 °C without normal stress (top), and with 0.50 MPa normal stress (bottom).

Due to the improved bonding effects in tests with normal stress, a consistent improvement in fatigue behaviour is experienced. This is clearly shown in Figure F.14, where fatigue functions of bond type E at 10 °C and at three different normal stresses are summarized. For comparison purposes, the asymptotic failure criterion was also used for fatigue test without normal stress. As can be seen, increased normal stress leads to increased number of loading cycles at the same displacement amplitude. This ranking was also observed at 10 °C and 20 °C for all considered bond types.

The investigation of the influence of the normal stress on bond fatigue behaviour at 30 °C was limited because of the high axial (horizontal) deformation observed. This deformation is induced as a consequence of the constant compressive normal stress, which presses the double layered asphalt sample in a horizontal way (see testing frame, Figure F.4). Considering the small initial shear gap width of 1 mm, the axial deformation evolution was controlled and limited through a horizontal linear variable differential transformer. In case of an overall axial displacement exceeding 1 mm, the shear steel blocks holding the specimen would run against each other that would lead to the damage of the testing frame.

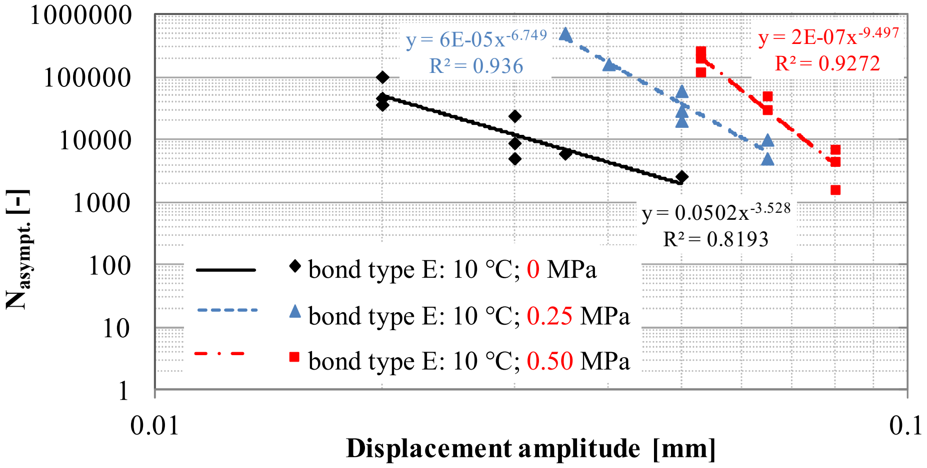

Figure F.14. Bond type E: fatigue functions at 10 °C and three normal stresses (0, 0.25 and 0.50 MPa).

Figure F.15 shows the testing frame before and after the breaking of one fatigue shear test, conducted on bond variant D at 20 °C, 0.50 MPa normal stress and 0.08 mm displacement amplitude. As can be seen, after stopping the test, the gap between shear rams is practically away. The gap reduction at the double layered asphalt sample is 0.7 mm (reduction from 1.1 to 0.4 mm).

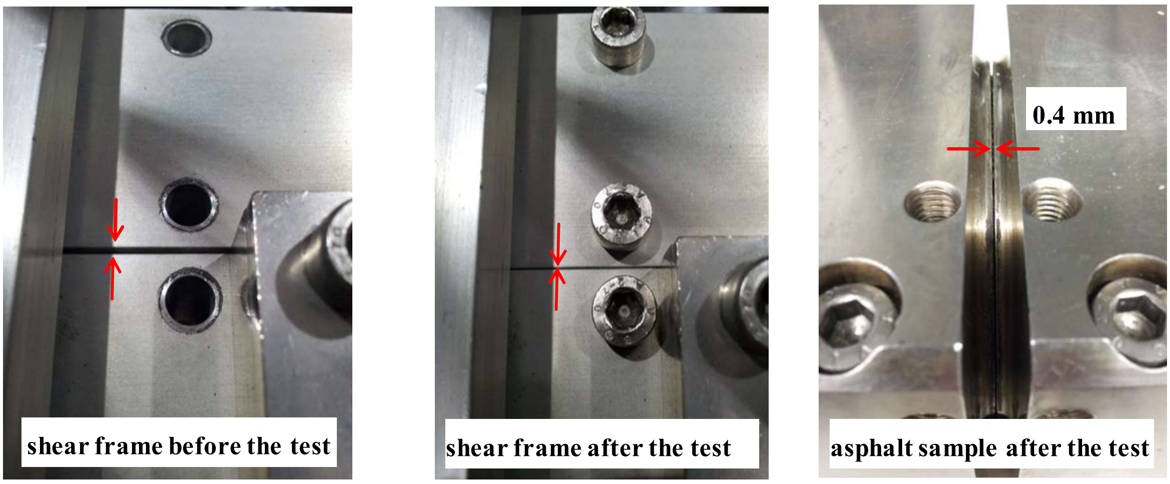

Figure F.15. Bond type D at 20 °C, 0.50 MPa normal stress and 0.08 mm displacement amplitude: shear frame before test (left), after the stopping of fatigue test (middle) and asphalt sample after testing.

Similar behaviour was observed for all bond types when subjected to normal stress at 30 °C, either during amplitude sweep tests or during fatigue tests. As a consequence, the test would be automatically stopped, without any possibility for bond fatigue evaluation.

Beside increased axial deformations at 30 °C, an increase for finely graded bond types C and D at 20 °C was also observed. An example is shown in Figure F.16, where one fatigue test was performed on bond type C at 20 °C, 0.25 MPa normal stress and 0.04 mm displacement amplitude. As can be seen, the axial deformation increases from the very beginning of the test. After the initial drop, the interface shear stiffness does not remain at the constant level as it would be expected, while it shows a slight increase of 2 MPa/mm. This indicates that increased axial deformation (0.28 mm, Figure F.16) leads to compression of the double layered sample and consequently to enhanced friction, adhesion and interlock at the shear interface. The consequence is an increased stiffness at the layers' interface.

This is a clear evidence of high influence of normal stress on fatigue behaviour of the asphalt layers' interface.

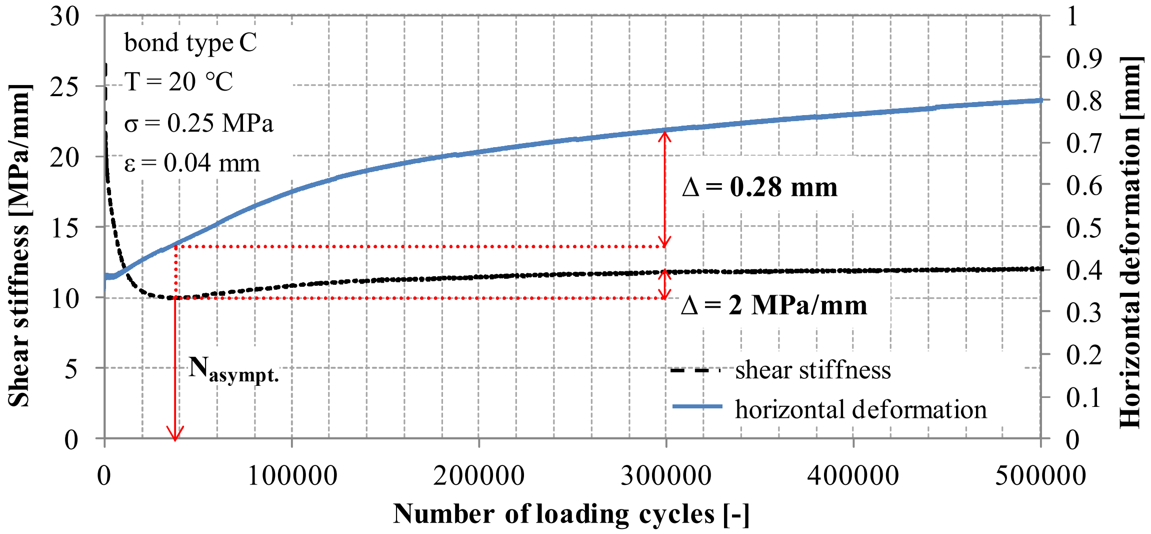

Figure F.16. Bond type C: interface shear stiffness and axial deformation over the number of loading cycles at 20 °C, 0.25 MPa normal stress and 0.04 mm displacement amplitude.

F.4.2.5 Temperature dependency

In order to investigate the influence of the temperature on interface shear fatigue behaviour, a wide temperature range was considered: 50, 30, 20, 10 and -10 °C. Figure F.17 shows four fatigue tests at -10 °C and 50 °C and at different normal stress levels. Shear fatigue tests at 50 °C show erroneous test results, since higher normal stress does not correspond to better fatigue life at the same displacement amplitude. On the other side, despite of the high displacement amplitude, the interface shear stiffness at -10 °C and 0 MPa normal stress does not show any decay after 450000 loading cycles. Higher number of loading cycles and higher displacement amplitudes could lead to the bond failure, but their application is time-consuming and would exceed the loading possibilities of the test frame. Based on this analysis, the evaluation of the bond fatigue properties at -10 °C and 50 °C is not recommended.

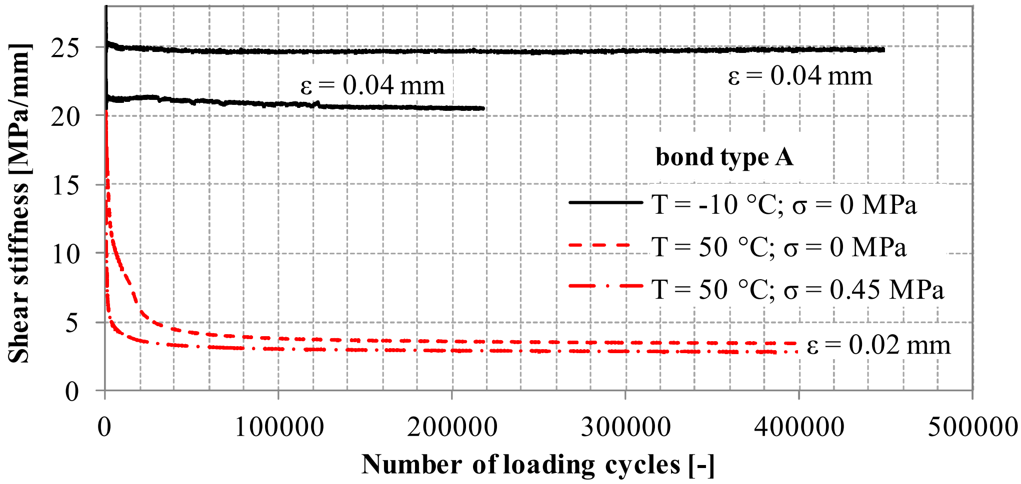

Figure F.17. Bond type A: shear fatigue tests at -10 °C and 50 °C at different normal stress levels.

Due to the different bond viscosities at 30, 20 and 10°C, the interface shear stiffness shows a remarkable temperature dependency. Lower temperatures lead to increased interface stiffness (see Figure F.10). Observing the fatigue lives at different test temperatures, the results for all bond types are not as consistent as for different normal stresses.

Independent on the normal stress level, the fatigue tests at 10 °C show for most bond types the best fatigue results. Fatigue tests at 20 °C and 30 °C show for different bond types different impacts. Considering fatigue tests without normal stress, bond types A and C show increased fatigue life with decreased temperature. One example for bond type A is shown in Figure F.18. On the other hand, bond type D exhibited better fatigue resistance at 30 °C compared to 20 °C. For bond type E, the fatigue temperature sensitivity between 10 °C and 20 °C is relatively low, because fatigue functions at this temperature range intersect.

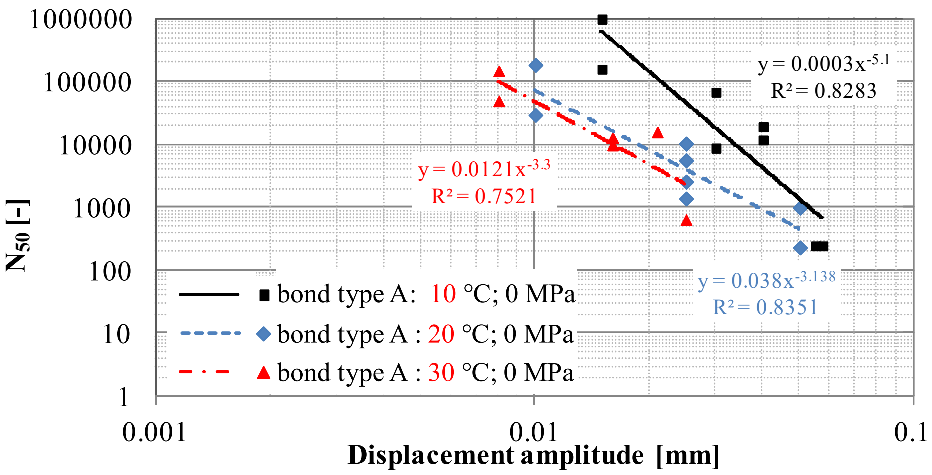

Figure F.18. Bond type A: fatigue functions at 0 MPa normal stress and three test temperatures (10, 20 and 30 °C).

As described in Section F.4.2.4, increased normal stress, and consequently the development of increased axial deformation, prevents the occurrence of fatigue shear tests at 30 °C. Only for bond type A at middle normal stress level (0.25 MPa) it was possible to compare fatigue functions at all three temperatures (see Figure F.19). As mentioned before, fatigue tests at 10 °C show the best results. Power functions at 20 °C and 30 °C intersect, where fatigue tests at 20 °C show better fatigue resistance at lower displacement amplitudes.

For other bond types the evaluation of the temperature influence in tests with normal stress was possible only at 10 °C and 20 °C. For most bond types the fatigue behaviour at 10 °C is better than at 20 °C. Exception is bond type C, where fatigue tests at 0.25 and 0.50 MPa normal stress show better results at 20 °C. For an applied normal stress of 0.50 MPa, the fatigue functions of bond type A at 20 °C and 30 °C intersect.

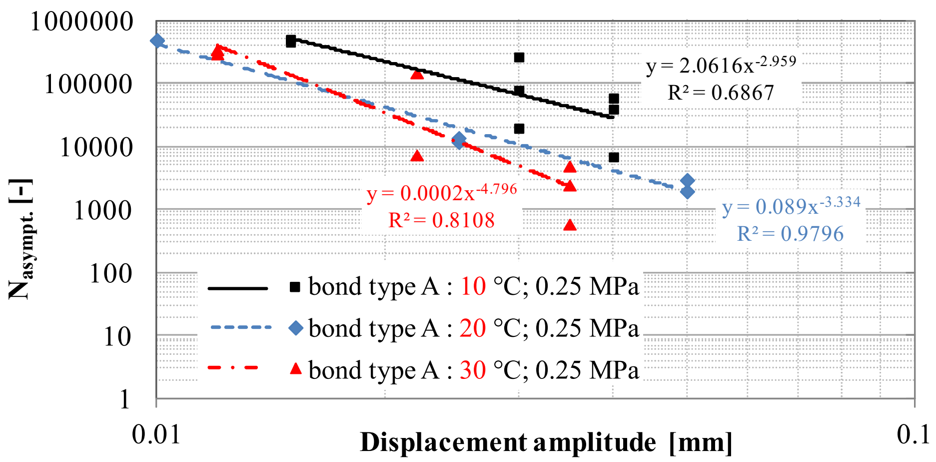

Figure F.19. Bond type A: fatigue functions at 0.25 MPa normal stress and three test temperatures (10, 20 and 30 °C).

F.4.2.6 Analysis and determination of the optimal test parameters

The determination of the optimal test parameters for direct shear test is done based on a validation analysis performed in previous research (Deysarkar and Tandon, 2005; Sholar et al., 2004; West et al., 2005), where all employed materials and test parameters were considered. Based on the asphalt mixtures and emulsion types used in this research the following experience should be reflected in the test results:

- Smaller nominal maximum aggregate size (NMAS) mixes benefit more from tack coat application compared to higher NMAS (Sholar et al., 2004; West et al., 2005). Based on this, the fatigue resistance of the double-layered specimens composed of surface and binder course material should be higher than the resistance of specimens composed of binder and base course or just base course material.
- Emulsions with higher asphalt binder content lead to increased bond strengths at the same application rate (Deysarkar and Tandon, 2005). Taking into account the emul-

sion types used in this work, the double layered specimens prepared with C40 (40 M.-% binder content) should show the worse fatigue resistance.

Based on the above-listed research findings the following ranking of the considered bond types with respect to shear fatigue resistance is to be expected (from best to worst): bond type C (lowest NMAS with polymer modified emulsion with 60 M.-% of asphalt binder) should give the best fatigue results; it should be followed by type D (lowest NMAS with emulsion with 40 M.-% of asphalt binder) and type A (middle NMAS with polymer modified emulsion with 60 M.-% of asphalt binder); the lowest fatigue resistance is expected for type E (highest NMAS with emulsion with 60 M.-% of asphalt binder) and type B (middle NMAS with emulsion with 40 M.-% of asphalt binder).

Considering shear fatigue tests for different bond types the following was found:

- The results at 0.50 MPa normal stress do not show the expected ranking because at 10 °C fatigue functions of type C (with lowest NMAS) and type E (with highest NMAS) intersect. Similar trend is obtained for tests at 20 °C, in the case of bond type A (with middle NMAS) and E (with highest NMAS).
- The results at 0.25 MPa normal stress do not exhibit the expected ranking because at 10 °C bond type D with lower emulsion's asphalt binder content (40 M.-%) show better fatigue resistance than type C with 60 M.-% of asphalt binder in emulsion. Similar to the results at 0.50 MPa and 20 °C the fatigue functions of bond type A and D intersect.
- The results at 0 MPa normal stress show for all considered temperatures the expected bond type ranking.

The possible reason for different bond types ranking in tests with normal stress application is most likely the significant accumulation of axial deformation observed in the present research. As this deformation is not entirely controllable and material composition dependent, it leads to different fatigue behaviour of the layers' interfaces.

As specified, tests without normal stress application lead to expected bond ranking. One example is shown in Figure F.20, where power functions of all bond types at 20 °C and 0 MPa normal stress are summarized.

As expected, the fine graded bond type C with polymer modified emulsion shows the best fatigue performance, while the fatigue functions of bond types A and D intersect. This indicates that the use of emulsion with high amount of asphalt binder can compensate the effect of the asphalt gradation. The coarse graded bond type E shows better fatigue properties compared to type B. The relatively low binder content in the base course, combined with low asphalt binder content of emulsion (40 M.-%), cannot compensate the favorable properties of finer graded mixture (compared to bond type E).

Based on these results, it can be stated that the proposed shear test can be successfully used for fatigue evaluation of the layers' interfaces. In order to avoid the axial deformation development in the specimen, it is highly recommended to perform the test without normal stress application on a routine basis. This is because the accumulation of permanent deformation may result into erroneous measurements and, potentially, misleading conclusions. While in the laboratory a static normal stress is applied, the pavement in the field experiences a cyclic dynamic normal load with stress field varying over time and location. If necessary, the normal stress can be applied at lower temperatures.

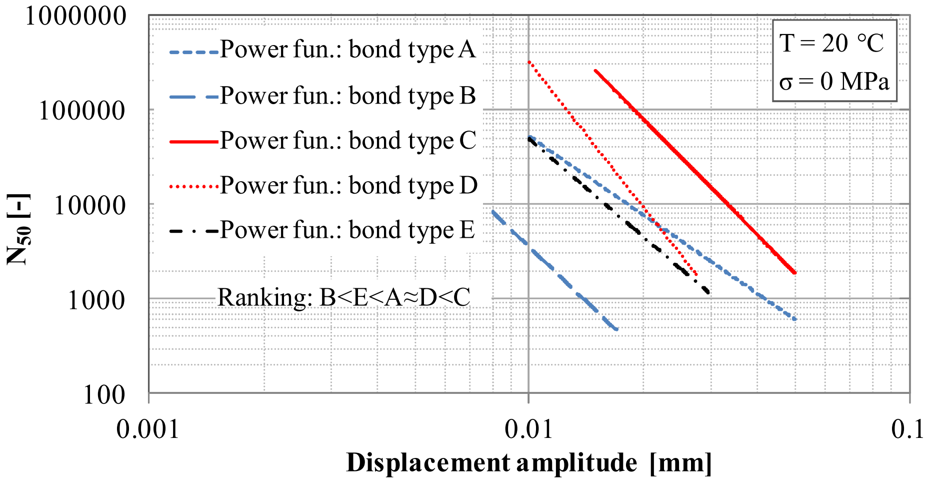

Figure F.20. Fatigue functions at 0 MPa normal stress at 20 °C for all considered bond variants.

F.5 Summary, conclusions and recommendations

In this paper, the fatigue properties of asphalt mixture layers' interfaces were investigated. The main objective of this work was to clarify if the direct shear test apparatus, presented in this paper, can be successfully used for the fatigue evaluation of the interface bond. For this purpose, over 400 amplitude sweep tests and fatigue tests were performed on different bond types, over a range of temperatures and normal stress levels. Based on the research results, the following conclusions can be drawn:

- Due to the constant decrease of shear stiffness in amplitude sweep tests, no linear viscoelastic behaviour can be observed for the specific loading conditions. It was shown that amplitude sweep test is a good experimental approach for obtaining the input parameters for fatigue tests.
- Because of the continuous cyclic loading in shear fatigue tests, the gradually decrease of the interface shear stiffness was confirmed. In tests without normal stress a three-stage behaviour was observed (similarly to the conventional fatigue tests). On the other side, the normal stress application leads to a specific stiffness evolution.
- Based on fatigue tests at three different shear amplitude levels with three test replicates, unique fatigue functions for the investigated asphalt mixture types were identi-

fied. The regressions of the resulting fatigue functions are relatively good, with 81 % of the functions having determination coefficient over 0.7.

- Bond fatigue properties are highly dependent on the normal stress application, and increase as the normal stress increases. This is a direct consequence of the enhanced friction, adhesion and interlock at the shear interface. Investigation on normal stress influence was limited to 30 °C, because of the deformation accumulation at the layers' interface. This deformation is induced as a consequence of the constant normal stress, which compresses the double-layered asphalt sample in an axial way and leads, at lower temperature, to increased stiffness of the layers' interface.
- Due to the different bond viscosities at the selected testing temperatures, the interface shear stiffness shows a remarkable high dependency, where decreased temperatures lead to increased interface shear stiffness. Independent on the normal stress level, the fatigue tests at 10 °C show for most bond types the best fatigue results, but also the highest scattering. Fatigue tests at 20 °C and 30 °C show a different impact for the various bond types.
- The validation of the test results was conducted, based on fatigue tests on different bond materials. It was found that tests without normal stress application can successfully reflect the research and practice experience.

Based on this preliminary work on asphalt bond, it can be stated that the proposed direct shear test can be successfully used for fatigue evaluation of the layer interfaces. In order to avoid the axial deformation development in the specimen, it is highly recommended to perform the test without normal stress application on a routine basis. Test temperature of 20 °C should be used, in order avoid the results scattering at lower temperatures.

Further work is needed in order to improve the results repeatability. The shear gap of 1 mm does not seem to be appropriate, especially when mixtures with high NMAS are used. This is the objective of a current research effort at Technische Universität Braunschweig.

F.6 References

Carr, A.G. 2001. The behaviour of layered pavement structures: The dynamic shear box. Project Report NCPE, University of Nottingham, UK.

Crispino, M., Festa, B., Giannattasio, P., and Nicolosi, V. 1997. Evaluation of the interaction between the asphalt concrete layers by a new dynamic test. Proc., 8th International Conference on Asphalt Pavements, Aug. 10-14, 1997, Seattle, Washington DC, USA.

Deysarkar, I., and Tandon, V. 2005. Field evaluation of tack coat quality measurement equipments. International Journal of Pavement Engineering, Vol. 4(1-2), pp. 25-37.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundstrom, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Diakhate, M., Millien, A., Petit, C., Phelipot-Mardele, A., and Pouteau, B. 2011. Experimental investigation of tack coat fatigue performance: Towards an improved lifetime assessment of pavement structure interfaces. Journal of Construction and Building Materials, Vol. 25(2), pp. 1123-1133.

Donovan, E., Al-Qadi, I., and Loulizi, A. 2000. Optimization of tack coat application rate for geocomposite membrane on bridge decks. Transportation Research Record, Journal of the Transportation Research Board, No. 1740, pp. 143-150.

FGSV, TP Asphalt-StB, Teil 33. 2007. Herstellung von Asphalt-Probeplatten im Laboratorium mit dem Walzsektor-Verdichtungsgerät (WSV). FGSV-Verlag, Forschungsgesellschaft fur Strasen- und Verkehrswesen, Köln, Germany.

FGSV. TP Asphalt-StB. Teil 80. 2012. Abscherversuch. FGSV-Verlag, Forschungsgesellschaft fur Strasen- und Verkehrswesen, Köln, Germany.

Gorszczyk, J., and Malicki, K. 2012. Influence of the tack coat material on interlayer bonding properties in asphalt layers system. Proc., 4th European Pavement and Asset Management Conference, EPAM, Sept. 5-7, 2012, Malmo, Sweden.

Hopman, P., Kunst, P., and Pronk, A. 1989. A renewed interpretation model for fatigue measurement. verification of Miner´s rule. Proc., 4th Eurobitumen Symposium, Oct. 4-6, 1989, Madrid.

Raab, C., and Partl, M. 2004. Interlayer shear performance: Experience with different pavement structures. Proc., 3rd Eurasphalt and Eurobitumen Congress, May 12-14, 2004, Vienna.

Romanoschi, S., and Metcalf, J. 2001. The characterization of asphalt concrete layer interfaces. Transportation Research Record, Journal of the Transportation Research Board, No. 1778, pp. 132-139.

Rowe, G.M., and Bouldin, M. G. 2000. Improved techniques to evaluate the fatigue resistance of asphaltic mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, Sept. 20-22, 2000, Barcelona, Spain.

Sanders, P.J. 2001. Reinforces asphalt overlays for pavements. Thesis, University of Nottingham, UK.

Santagata, E., and Canestrari, F. 1994. Tensile and shear tests of interfaces in asphalt mixes: A new prospective on their failure criteria. Proc., 2nd International Symposium on Highway Surfacing, Ulster, Northern Ireland.

Sholar, G. A., Page, G. C., Musselman, J. A., Upshaw, P. B., and Moseley, H. L. 2004. Preliminary investigation of a test method to evaluate bond strength of bituminous tack coats. Journal of the Association of Asphalt Paving Technologists, Vol. 73, pp. 771-806.

Tozzo, C., D'Andrea, A., Cozzani, D., and Meo, A. 2014. Fatigue investigation of the interface shear performance in asphalt pavement. Journal of Modern Applied Science, Vol. 8(2), pp. 1-12.

Weber, R. 1991. Die Rißbildung in Asphaltstraßen als Folge mangelhaften Schichtenverbundes (Dissertation). Prüfamt fur Bau von Landverkehrswegen, Technische Universitat München, Germany.

Wellner, F., and Ascher, D. 2007. Untersuchung zur Wirksamkeit des Haftverbundes und dessen Auswirkung auf die Lebensdauer von Asphaltbefestigungen (Schlussbericht, AiF Forschungsvorhaben Nr. 13589 BR/1). Professur fur Strasenwesen, Technische Universität Dresden.

West, R. C., Zhang, J., and Moore, J. 2005. Evaluation of bond strength between pavement layers (NCAT Report 05-08). National Center for Asphalt Technology, University of North Carolina, USA.

Wheat, M. 2007. Evaluation of bond strength at asphalt interfaces. Master thesis, Kansas State University, USA.

Wistuba, M., Isailović, I., and Buchler, S. 2016. Zyklische Schersteifigkeits- und Scherermüdungsprüfung zur Bewertung und Optimierung des Schichtenverbundes in Straßenbefestigungen aus Asphalt (Schlussbericht Nr. 17634 BG/2. i. A. der AIF). Institut für Straßenwesen, Technische Universität Braunschweig.

Woods, M. E. 2004. Laboratory evaluation of tensile and shear strengths of asphalt tack coats. Master thesis, Mississippi State University, Starkville, USA.

Zofka, A., Maliszewski, M., Bernier, A., Josen, R., Vaitkus, A., and Kleiziene, R. 2015. Advanced shear tester for evaluation of asphalt concrete under constant normal stiffness conditions. Journal of Road Materials and Pavement Design, Vol. 16, pp. 187-210.

G Asphalt mixture layers' interface bonding properties under monotonic and cyclic loading[7]

Abstract: This paper focuses on investigating the interface shear bonding properties of asphalt pavement structures using both monotonic and cyclic direct shear tests. Several pavement structures were considered, differing in the asphalt mixture type and tack coat type, and laboratory preparation of the double-layered asphalt specimens. Based on the results on bond materials used in this research, it was found that the resulting shear strength from monotonic shear test can be used only as a rough indicator for long term interface bonding performance, because not all research and field experience could be reflected in the test results. The cyclic shear test employed in this study can be used for evaluating the interface fatigue performance. Additionally, differentiation between particular bond materials with respect to interface shear bonding properties is assured.

Keywords: interface shear bonding properties, monotonic shear test, cyclic shear test.

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[7] Isailović, I., and Wistuba, M. 2018. Asphalt mixture layers' interface bonding properties under monotonic and cyclic loading. Published in Journal of Construction and Building Materials, Vol. 168, pp. 590-597, DOI: 10.1016/j.conbuildmat.2018.02.149, Elsevier.

Own contribution to:

- conception: 100 %
- realization: 100 %
- formulation: 90 %

G.1 Introduction

Asphalt pavement structures are usually composed of at least two asphalt layers which are successively paved and commonly bonded using bituminous tack coat material. The prevailing interface bonding properties highly influence the long-term performance and durability of asphalt pavements (Tozzo et al., 2014).

Good bonding between asphalt layers ensures that the layers work as a composite structure in order to withstand traffic and environmental loading (Sutanto, 2009). On the other hand, poor or missng bonding between asphalt layers can affect the redistribution of stresses and strains in the pavement structure, leading to premature failure (Romanoschi and Metcalf, 2001). This can result in a slippage cracking of the surface layer, or in loss of bearing capacity of the whole pavement structure.

Interface bonding characteristics in asphalt pavement structures are mostly evaluated using monotonic shear test methods, which number has been raised over the years (Leutner, 1979; Sholar et al., 2004; Santagata and Canestrari, 2004; Raab and Partl, 2004; West, 2005; Tozzo et al., 2014). Usually, the monotonic shear test consists of applying a constant shear displacement rate across the layers' interface, where shear strength is obtained at the peak shearing force. However, it is not clear if the so obtained shear strength can be used as an indicator for long-term interface shear performance, because the generated shear stress is not cyclic. Furthermore, the test results cannot be appropriately used for modeling or for mechanistic pavement design purposes.

In order to overcome disadvantages of monotonic shear testing some research effort has been put in the development of more complex cyclic shear tests, which are partially able to simulate the field conditions more realistically (Crispino et al., 1997; Carr, 2001; Romanoschi and Metcalf, 2001; Sanders, 2001; Diakhate et al., 2011; Gorszczyk and Malicki, 2012; Tozzo et al., 2014; Wellner and Hristov, 2016; Isailović et al., 2017). The difference between cyclic shear tests is mainly attributed to different interface loading conditions.

G.2 Objective and research approach

The objective of this work is to investigate if the shear strength obtained from monotonic shear tests can be used as an indicator for the long-term interface shear performance, as observed under cycling loading. For that purpose, direct monotonic shear test introduced by Leutner (1979), and direct cyclic shear fatigue procedure introduced by Isailović et al. (2017) were used. In order to determine the displacement amplitudes for shear fatigue tests, cyclic shear amplitude sweep tests were additionally performed. Several pavement structures (with different types of bonding) were considered, differing in the asphalt mixture type and tack coat type, and laboratory preparation of the double-layered asphalt specimens. Figure G.1 shows the selected research approach.

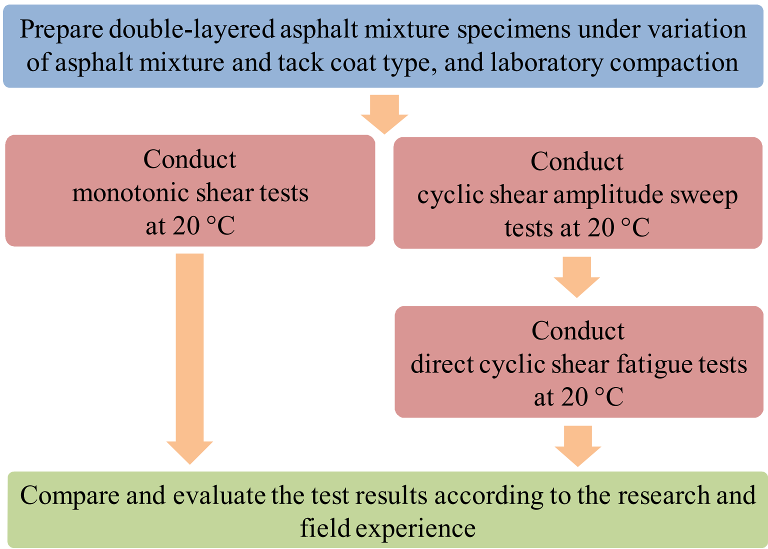

Figure G.1. Flow chart of the selected research approach.

G.3 Experimental study

G.3.1 Material composition and specimen preparation

Double-layered asphalt specimens for both cyclic and monotonic tests were prepared using three different asphalt mixture types:

- asphalt concrete AC 22 T S with maximum grain size 22 mm, usually used as base course material on highly trafficked road pavements,
- asphalt concrete AC 16 B S with maximum grain size 16 mm, usually used as binder course material on highly trafficked road pavements, and
- stone mastic asphalt SMA 11 S with maximum grain size 11 mm, usually used as wearing course material on highly trafficked road pavements.

Figure G.2 and Table G.1 represent the grain size distribution and composition of the used asphalt mixtures respectively.

Table G.1: Composition of asphalt mixtures

Characteristic	Asphalt mixture type		
	AC 22 T S	**AC 16 B S**	**SMA 11 S**
Aggregate type	limestone	basalt	basalt
RAP addition [%]	30	0	0
Binder type	50/70	25/55-55	25/55-55
Binder content [%]	4.1	4.7	6.0
Bulk density [g/cm^3]	2.374	2.475	2.461
Air voids content [%]	7.4	6.5	3.9

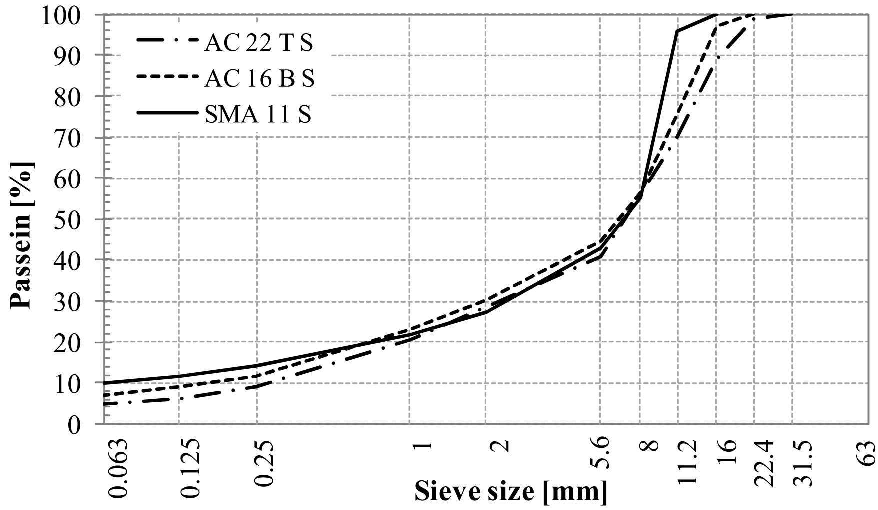

Figure G.2. Grain size distribution for asphalt mixtures: AC 22 T S, AC 16 B S, and SMA 11 S.

From these materials double-layered asphalt slabs were fabricated in laboratory in three steps using segmented steel roller compaction method (Wistuba, 2014) (Figure G.3): (i) compaction of the lower slab layer, (ii) application of the tack coat, and (iii) compaction of the upper slab layer after breaking process of tack coat occurred. This compaction procedure is defined as ''hot over cold'' compaction.

Three types of bituminous interface tack coat materials were used:

- cationic polymer modified emulsion **C60**BP1-S with 60 mass% of bitumen content,
- cationic emulsion **U60K** with 60 mass% of bitumen content, and
- cationic emulsion **C40**BF1-S with 40 mass% of bitumen content.

Hot over cold compaction:

- compaction of lower slab layer (pre- and main-compaction phase),
- application of the tack coat after 24 hours,
- compaction of upper slab layer (pre- and main-compaction phase) after 3 hours.

Hot over hot compaction:

- compaction of lower slab layer (only pre-compaction phase),
- immediate compaction of upper slab layer (pre- and main-compaction phase).

pre-compaction phase → displacement controlled
main-compaction phase → force controlled

Figure G.3. Segmented steel roller compaction (left) and description of compaction procedures.

Additionally, ”hot over hot” compaction was performed, where lower and upper asphalt layers were successively compacted in a short time, without tack coat application (Figure G.3). The lower slab layer was compacted in displacement controlled pre-compaction mode with low energy in order to avoid over-compaction. Consequently, additional compaction was provided by immediate compaction of the upper slab layer. For this method a better interlocking of the asphalt layers is guaranteed.

After slab compaction, double-layered samples were drilled from the slabs, with 99 mm diameter for cyclic tests and with 150 mm diameter for monotonic tests.

Based on various asphalt mixture and tack coat types, and laboratory preparation of the double-layered asphalt specimens, 10 different bond types were considered in total. Table G.2 gives an overview of the applied layer-bond combinations and their composition.

Table G.2: Combinations of layers and interface tack coat materials and laboratory preparation to produce different bond types

Bond type	Layer materials	Laboratory preparation	Emulsion type	Application rate of emulsion [g/m²]	Thickness of asphalt layers [cm]
A	AC 16 B S on AC 22 T S	HOT over COLD	C60BP1-S	300	5 cm on 6 cm
B			C40BF1-S		
C	SMA 11 S on AC 16 B S		C60BP1-S	200	4 cm on 5 cm
D			C40BF1-S		
E	AC 22 T S on AC 22 T S		U60K	300	6 cm on 6 cm
F	AC 22 T S on AC 22 T S	HOT over HOT	-	-	6 cm on 6 cm
G	AC 16 B S on AC 16 B S				5 cm on 5 cm
H	SMA 11 S on SMA 11 S				4 cm on 4 cm
I	AC 16 B S on AC 22 T S				5 cm on 6 cm
J	SMA 11 S on AC 16 B S				4 cm on 5 cm

G.3.2 Monotonic shear test

Monotonic shear test introduced by Leutner (1979) relies on a simplified shear apparatus (see Figure G.4), where one layer of double layered asphalt test sample is fixed during the test, and the other layer is loaded vertically in a displacement controlled mode. A constant shear displacement rate of 50 mm/min is applied across the layers’ interface until failure. The test is performed on a 150 mm diameter core specimen, and at fixed temperature of 20 °C.

Figure G.4. Monotonic shear test device.

During the whole test duration, displacement and shear force are continuously recorded using a data acquisition system. Shear strength is defined as peak of the shear force (cp. τ_{max}, Figure G.5). Usually, two replicates per bond type are tested.

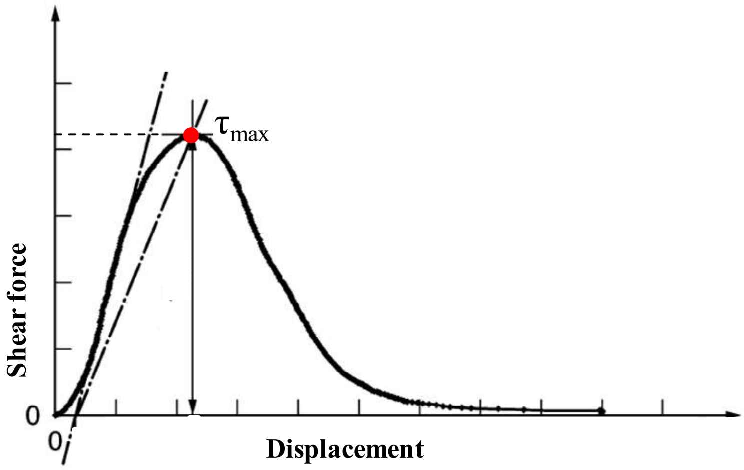

Figure G.5. Shear force over displacement in direct monotonic shear test.

G.3.3 Cyclic shear fatigue test

Cyclic shear fatigue procedure used in this study (Isailović et al., 2017) relies on a direct shear test, which is actually a cyclic version of the monotonic shear test introduced by Leutner (1979).

The cyclic shear frame is installed in a standard servo-hydraulic testing device. For satisfactory and precise allocation of the sample inside the frame, the double-layer cylindrical specimen is glued within four steel half-shells (see Figure G.6). The gap width that is exposed to direct cyclic shear stress is set to 1 mm. The testing frame is presented in Figure G.7.

While one pair of half-shell is fixed during the test, the other pair is loaded vertically in a displacement controlled mode. Sinusoidal cyclic shear load is applied at a fixed frequency of 10 Hz, and at a fixed temperature of 20 °C. For controlling the vertical shear displacement, two strain gauges are attached to both sides of the test frame.

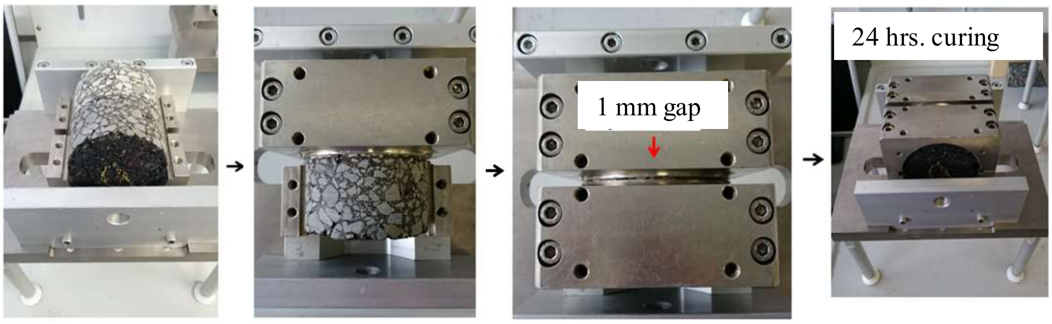

Figure G.6. Double-layered cylindrical specimen glued within four steel half-shells.

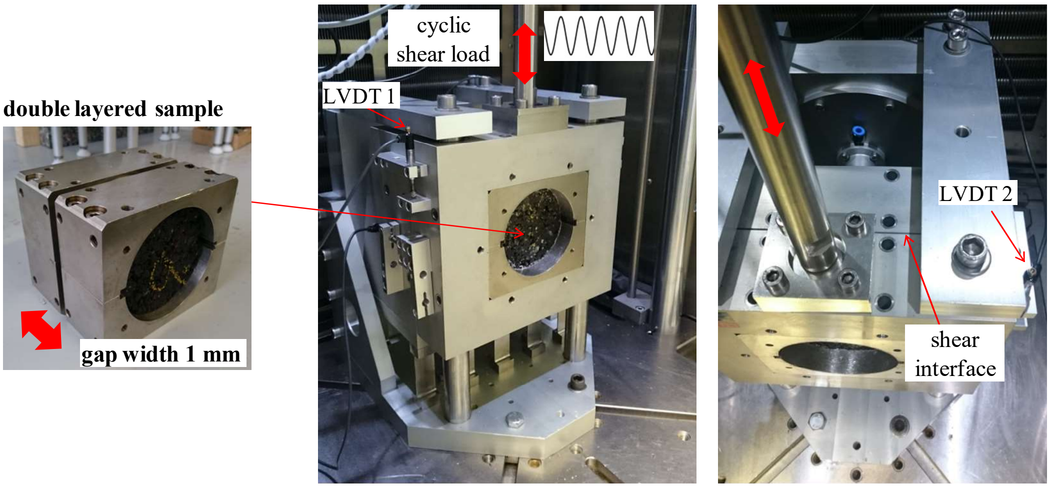

Figure G.7. Cyclic shear test device.

During the cyclic shear fatigue test, displacement and force are continuously recorded using a data acquisition system. Resulting shear stresses are calculated, reading

$$\tau_n = \frac{F_n}{A_{eff}} \quad \text{[MPa]}, \tag{G.1}$$

where: τ_n = shear stress at the n^{th} cycle [MPa]; F_n = force amplitude at the n^{th} [N], and A_{ff} = interface area [mm^2].

Interface shear stiffness is determined from the ratio between shear stress and relative displacement at the interface, reading

$$K_{s,n} = \frac{\tau_n}{U_n} \quad \text{[N/mm}^3\text{]}, \tag{G.2}$$

where: $K_{s,n}$ = interface shear stiffness at the n^{th} cycle [MPa/mm]; τ_n = shear stress at the n^{th} cycle [MPa], U_n = displacement amplitude at the n^{th} cycle [mm].

Referring to classical fatigue tests performed on asphalt mixtures, a conventional failure criterion was used for reporting (Di Benedetto et al., 2004). This is related to the number of loading cycles at failure (fatigue life, N_{50}), where 50 % decrease in interface shear stiffness occurs. The initial interface shear stiffness is defined at the loading cycle where defined displacement amplitude was achieved (approximately after 100 loading cycles). Based on fatigue lives at three different shear displacement amplitudes with three test repetitions (9 tests in total), the characteristic interface shear fatigue curves were drawn, reading

$$U = C_1 \cdot N_{50}^{C_2} \tag{G.3}$$

where: U = displacement amplitude [mm], N_{50} = number of loading cycles at failure [-], and C_1, C_2 = function parameters [-].

Displacement amplitudes for shear fatigue testing were evaluated in pre-testing procedure using an amplitude sweep test (see Figure G.8). This test consists of a stepwise increase of the shear displacement amplitude from 0.008 mm to 0.2 mm. Up to 25 loading sequences were applied, each consisting of 200 cycles. Based on these test results, a particular displacement amplitude range can be defined, where an effective fatigue evaluation is possible.

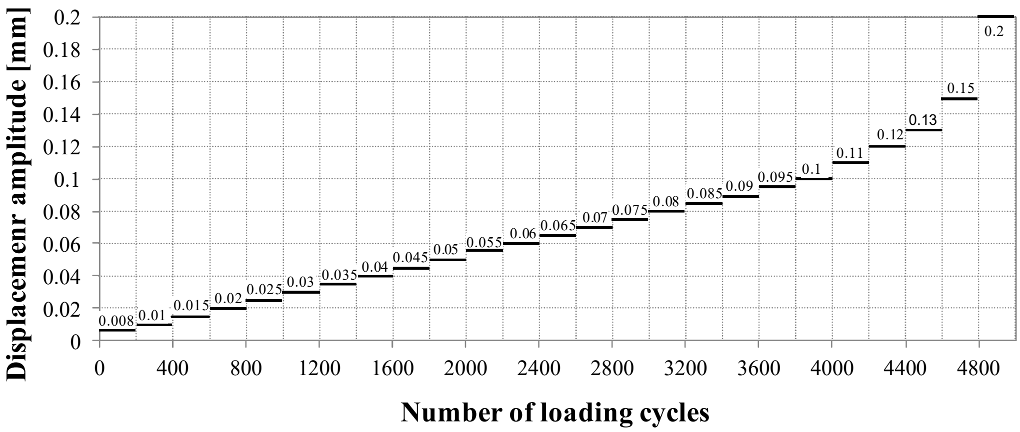

Figure G.8. Principle of amplitude sweep test.

G.4 Experimental results

G.4.1 Monotonic shear test

The mean shear strengths, calculated from two monotonic shear tests are presented in Figure G.9 for each bond type. According to the test results, a relatively low scattering of test results for one bond type is observed.

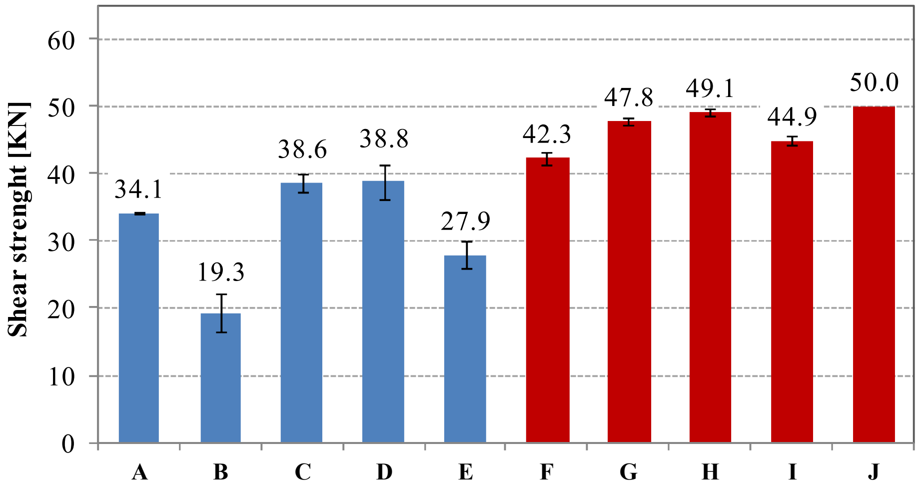

Figure G.9. Mean shear strengths (from two monotonic shear tests) of considered bond types.

G.4.2 Cyclic shear fatigue test

For each bond type employed (cp. Table G.2), two cyclic shear amplitude sweep tests were performed.

Figure G.10 shows one example of amplitude sweep test conducted for bond type I. With increasing displacement amplitude, the interface shear stiffness decreases gradually until interface bonding failure. The nominal force required for achieving a specific displacement amplitude increases up to a maximum limit value, thereafter a significant reduction of force is observed.

The displacement amplitude at which a disproportional sudden drop in force amplitude occurs can be considered as a limit for shear fatigue tests (compare vertical dashed line in Figure G.10), since this would imply a very short fatigue life. Therefore, the maximum displacement amplitude for fatigue tests should be selected in range below the identified limit. Consequently, for the amplitude sweep test presented in Figure G.10, the following displacement amplitudes were selected for shear fatigue tests: 0.035 mm, 0.05 mm, and 0.065 mm (cp. Figure G.10).

In Table G.3 the displacement amplitudes applied for all other bond types are shown.

Table G.3: Displacement amplitudes applied in shear fatigue tests for all bond types (A-J)

Bond type	Displacement amplitude [mm]	Bond type	Displacement amplitude [mm]
A	0.01 / 0 025 / 0.05	**F**	0.02 / 0.03 / 0.045
B	0.008 / 0.012 / 0.016 (0.017)	**G**	0.025 / 0.04 / 0.06
C	0.015 / 0.035 / 0.05	**H**	0.05 / 0.07 / 0.085
D	0.01 / 0.02 / 0.028	**I**	0.035 / 0.05 / 0.065
E	0.01 (0.015) / 0.02 / 0.03	**J**	0.045 / 0.06 / 0.075

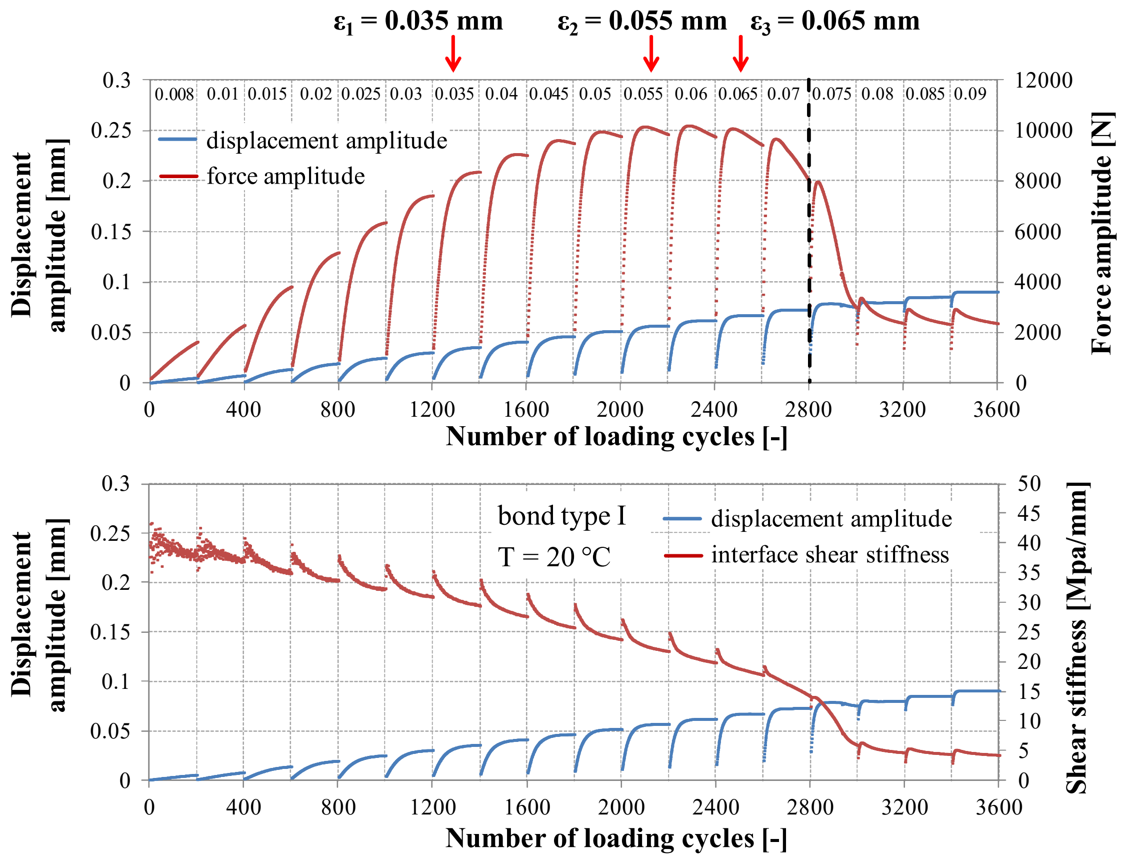

Figure G.10. Bond type I: Evolution of the displacement amplitude, interface shear stiffness, and force amplitude in cyclic shear amplitude sweep test at 20 °C.

Figure G.11 (left) represents one example of the interface shear stiffness evolution in shear fatigue test, conducted for bond type I at 0.035 mm displacement amplitude. Similarly to the conventional fatigue tests, three phases of the stiffness decay can be distinguished (Di Benedetto, 2004): initiation phase with a rapid decrease in interface shear stiffness, quasi-stationary phase of the interface shear stiffness decay, and propagation phase. After the propagation phase, the interface shear stiffness remains at a very low level. This is most probably attributed to the residual friction within the layer interface.

Based on the test results (N_{50}) at three different displacement amplitudes, the characteristic interface shear fatigue curve can be drawn (Figure G.11, right). Increased displacement amplitude leads to the decreased resulting fatigue life.

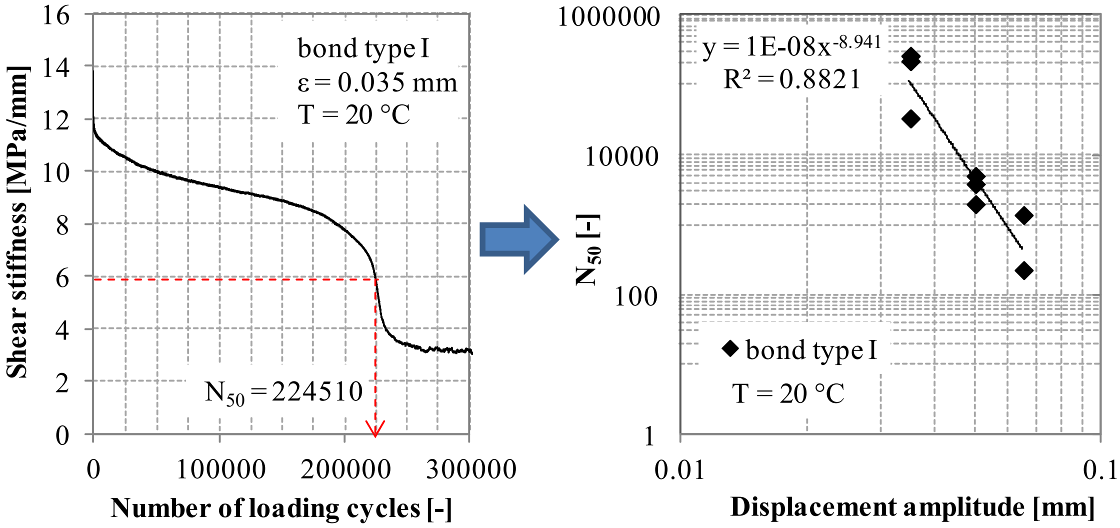

Figure G.11. Bond type I: evolution of interface shear stiffness in cyclic shear fatigue test at 0.0.35 mm displacement amplitude (left), and interface shear fatigue curve obtained from fatigue tests at three different displacement amplitudes (right).

Based on approximately 90 single fatigue tests, the resulting shear fatigue performance curves (power functions) and function parameters for all considered bond types were drawn (see Figure G.12 and Table G.4, respectively). Regression functions were found without considering outliers.

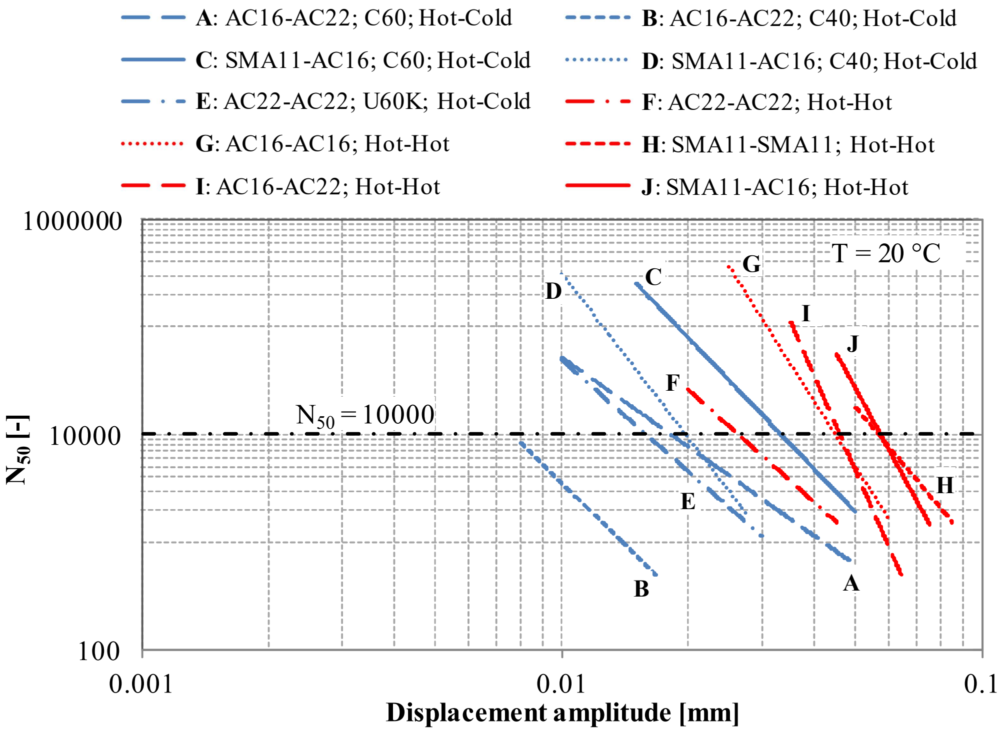

Figure G.12. Resulting shear fatigue curves for all in Table G.2 considered bond types.

Table G.4: Resulting power function parameters (k_1 and k_2) and sum of squares (R^2) for all in Table G.2 considered bond types

Power function: $N_{50} = k_1 \cdot U^{-k_2}$ ($k_{1,2}$ = regression parameters; U = displacement amplitude)							
Bond type	**k_1**	**k_2**	**R^2**	**Bond type**	**k_1**	**k_2**	**R^2**
A	0.1548	2.7628	0.83	**F**	0.0307	3.4875	0.84
B	0.0001	3.8226	0.71	**G**	4.58E-5	6.1773	0.93
C	0.0095	4.0719	0.88	**H**	0.0182	4.6049	0.79
D	2.06E-5	5.0916	0.80	**I**	1.07E-8	8.9409	0.88
E	0.0066	3.4356	0.89	**J**	1.27E-5	7.1653	0.87

G.4.3 Discussion of results

In order to allow reliable comparison between monotonic and cyclic shear tests used, the number of loading cycles at failure N_{50} = 10000 in cyclic tests is selected, where the corresponding displacement amplitudes were calculated for each bond type.

Based on resulting shear strengths from monotonic shear tests (lower shear strength implies lower interface bonding), and based on the calculated displacement amplitudes at N_{50} = 10000 from cyclic shear fatigue tests (lower displacement amplitude implies lower interface bonding), the considered bond types can be ranked with respect to interface shear bonding properties, as proposed in Figure G.13.

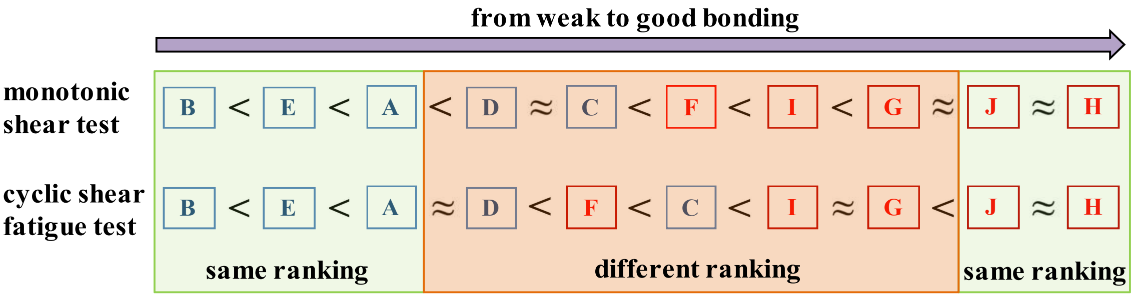

Figure G.13. Bond type ranking in monotonic shear test (based on resulting shear strengths) and in cyclic shear test (based on calculated displacement amplitudes at N_{50} = 10000).

According to the best practise and research experience (Sholar et al., 2004; Muench and Moomaw, 2008; Sutanto, 2009) the cyclic shear fatigue test led to expected bond type ranking:

- The ''hot over hot'' compacted double-layered asphalt samples show, except for bond type F, better interface shear bonding performance when compared to ''hot over cold'' compaction. This is most probably a consequence of aggregate interlocking effects of the two asphalt layers.
- Because of the smaller nominal maximum aggregate size and better aggregate adjustment, asphalt samples composed of surface and binder course material show higher fatigue resistance compared to bond types composed of binder and base course or just

base course material (compare bond types: J > I > F; C > A; D > B, fabricated with the same tack coat material).

- Bond types with polymer modified tack coat material and with the higher tack coat bitumen content show favourable interface shear bonding performance, if comparing all ‘‘hot over cold” fabricated bond types (compare bond types: C > D; A > B).

By comparing the bond type ranking from monotonic and from cyclic shear tests (Figure G.13), the following conclusions can be drawn. The monotonic shear test can differentiate between some bond variants in range of weak or good interface bonding (Figure G.13, bond variants B, E A, and bond variants J, H, respectively), but for some specific material and production variations the results are not clear. For example, bond type D shows in monotonic shear test similar shear strength compared to bond type C, although low quality non-polymer modified tack coat material with only 40 % by mass of bitumen was used. Furthermore, better distinguishing between bond variants G, I, J with different nominal maximum aggregate size could not be achieved, as good as in cyclic shear fatigue test.

G.5 Summary and conclusions

In this study, two methods for evaluation of the interface shear bonding properties of asphalt pavement structures were investigated and compared: direct monotonic shear test and direct cyclic shear fatigue test. In total, 10 bond types were considered, where asphalt mixtures for wearing, binder and base course, three different tack coat types, and two laboratory compaction methods of the double-layered asphalt specimens were employed.

Based on the numerous tests on bond materials used, the following conclusions can be drawn:

- The resulting shear strength from monotonic shear test cannot reflect the research and practice experience in total, as good as results from cyclic shear test.
- Therefore, shear strength from monotonic shear test can be used only as a rough indicator for long term interface bonding performance, because differences in bond types with some specific material and production variations cannot be recognized.
- The cyclic shear test can be used for interface fatigue (long term) evaluation, with better differentiating between particular bond materials. However, since shear fatigue test requests extended laboratory effort compared to monotonic shear test, it is not recommended to use it on a routine basis, as long as differentiating between specific bond materials in monotonic shear test is assured. Further work is needed in order to improve the results repeatability.

These findings are based on investigations of limited bond types only, and may be different for others.

G.6 References

Carr, A.G. 2001. The behaviour of layered pavement structures: The dynamic shear box. Project Report NCPE, University of Nottingham, UK.

Crispino, M., Festa, B., Giannattasio, P., and Nicolosi, V. 1997. Evaluation of the interaction between the asphalt concrete layers by a new dynamic test. Proc., 8th International Conference on Asphalt Pavements, Aug. 10-14, 1997, Seattle, Washington, USA.

Diakhate, M., Millien, A., Petit, C., Phelipot-Mardele, A., and Pouteau, B. 2011. Experimental investigation of tack coat fatigue performance: Towards an improved lifetime assessment of pavement structure interfaces. Journal of Construction and Building Materials, Vol. 25(2), pp. 1123-1133.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundström, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Gorszczyk, J., and Malicki, K. 2012. Influence of the tack coat material on interlayer bonding properties in asphalt layers system. Proc., 4th European Pavement and Asset Management Conference, EPAM, Sept. 5-7, 2012, Malmo, Sweden.

Isailović I., Cannone Falchetto A., and Wistuba M. 2017. Fatigue investigation on asphalt mixture layers' interface. Journal of Road Materials and Pavement Design, Vol. 18, sup4, pp. 514-534.

Leutner R. 1979. Untersuchung des Schichtenverbundes beim bituminösen Oberbau. Bitumen, Vol. 3, pp. 84-91.

Muench S., and Moomaw T. 2008. Debonding of hot mix asphalt pavements in Washington State: an initial investigation. Technical Report TNW 2008-10, Transportation Northwest (TransNow), University of Washington and Washington State Transportation Commission, USA.

Raab, C., and Partl, M. 2004. Interlayer shear performance: Experience with different pavement structures. Proc., 3rd Eurasphalt and Eurobitumen Congress, May 12-14, 2004, Vienna.

Romanoschi, S., and Metcalf, J. 2001. The characterization of asphalt concrete layer interfaces. Transportation Research Record, Journal of the Transportation Research Board, No. 1778, pp. 132-139.

Sanders, P.J. 2001. Reinforces asphalt overlays for pavements. Thesis, University of Nottingham, UK.

Santagata, E., and Canestrari, F. 1994. Tensile and shear tests of interfaces in asphalt mixes: A new prospective on their failure criteria. Proc., 2nd International Symposium on Highway Surfacing, Ulster, Northern Ireland.

Sholar, G. A., Page, G. C., Musselman, J. A., Upshaw, P. B., and Moseley, H. L. 2004. Preliminary investigation of a test method to evaluate bond strength of bituminous tack coats. Journal of the Association of Asphalt Paving Technologists, Vol. 73, pp. 771-806.

Sutanto M.H. 2009. Assessment of bond between asphalt layers. Thesis, University of Nottingham, UK.

Tozzo, C., D'Andrea, A., Cozzani, D., and Meo, A. 2014. Fatigue investigation of the interface shear performance in asphalt pavement. Journal of Modern Applied Science, Vol. 8(2), pp. 1-12.

Wellner F., and Hristov, B. 2016. The effect of interlayer bond on the service life of asphalt pavements. Proc., 4th Annual International Conference on Architecture and Civil Engineering, Global Science and Technology Forum (GSTF), Apr. 25-26, 2016, Singapore, pp. 444-449.

West, R. C., Zhang, J., and Moore, J. 2005. Evaluation of bond strength between pavement layers (NCAT Report 05-08). National Center for Asphalt Technology, University of North Carolina, USA.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

References

Airey, G.D., Rahimzadeh, B., and Collop, A.C. 2002. Linear viscoelastic limits of bituminous binders. Journal of the Association of Asphalt Paving Technologists, Vol. 71, pp. 89-115.

Airey, G.D. 2003. State o the art report on aging test methods for bituminous pavements. International Journal of Pavement Engineering, Vol. 4, pp. 165-176.

Arand, W. 1985. Influence of bitumen hardness on the fatigue behavior of asphalt layers. Proc., 3rd Eurobitume-Symposium, Vol. 1, pp. 164 - 167, Sept. 11-13, 1985, Den Haag, The Netherlands.

Ashouri, M. 2014. Modeling microdamage healing in asphalt pavements using continuum damage theory. Thesis, North Carolina State University, Raleigh, North Carolina, USA.

ASTM International. ASTM E1823 - 13. 2013. Standard Terminology Relating to Fatigue and Fracture Testing. Annual Book of ASTM Standards, vol. 03.01. American Society for Testing and materials, West Conshohocken, USA.

Ayar, R., Moreno-Navarro, F., and Rubio-Gamez, C. 2016. The healing capability of asphalt pavements: a state of the art review. Journal of Cleaner Production, Vol. 113, pp. 28-40.

Baaj, H., Di Benedetto, H., and Chaverot, P. 2003. Fatigue of mixes: an intrinsic damage approach. Proc., 6th RILEM Symposium PTEBM, Apr. 14-16, 2003, pp. 394-400, Zurich.

Babadopulos, L. 2017. Phenomena occurring during cyclic loading and fatigue tests on bituminous materials : Identification and quantification. Thesis, University of Lyon, France.

Barnes, H.A. 1997. Thixotropy-a review. Journal of Non-Newtonian Fluid Mechanics, Vol 70 (1–2), pp. 1-33.

Bell, C. 1989. Summary report on ageing of asphalt-aggregate systems (SHRP-A/IR-89-004). Project A-003A (Performance Related Testing and Measurement of Asphalt-Aggregate Interactions and Mixtures), Strategic Highway Research Program, National Research Centre, Washington, D.C.

Bhasin, A., Narayan, A., and Little, D. 2009. Laboratory investigation of a novel method to accelerate healing in asphalt mixtures using thermal treatment. Research report SWUTC/09/476660-00005-1, University of Texas, Austin, USA.

Bodin, D., Soenen, H., and De La Roche, C. 2004. Temperature effects in binder fatigue and healing tests. Proc., 3rd Eurasphalt and Eurobitume Congress, Book II, pp. 1996-2004, May 12-14, 2004, Vienna.

Bodin, D., Terrier, J.P., Perroteau, C., and Hornych, P. 2010. Effect of temperature on fatigue performance of asphalt mixes. Proc., Int. Symposium on Asphalt Pavements ISAP, Aug. 1-6, 2010, Nagoya, Japan.

Breysse, D., De La Roche, C., Domec, V., and Chauvin, J.J. 2003. Influence of rest time on recovery and damage during fatigue tests on bituminous composites. Journal of Materials and Structures, Vol. 36, pp. 648-651.

Breysse, D., Domec, V., Yotte, S., and De La Roche, C. 2005. Better assessment of bituminous materials lifetime accounting for the influence of rest periods. Journal of Road Material and Pavement Design, Vol. 6, pp. 175-195.

Büchler, S., Mollenhauer, K.,Wistuba, M., and Renken, P. 2009. Aging of stone mastic asphalt and evaluation of cracking resistance. Proc., 8th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields, University of Illinois at Urbana-Champaign, June 29-July 2, 2009, Champaign, Illinois, USA.

Canestrari, F., Ferrotti, G., Lu, V., Millien, A., Partl, M., Petit, C., Phelipot-Mardelé, A., Piber, H., and Raab, C. 2013. Advances in interlaboratory testing and evaluation of bituminous materials - Mechanical testing of interlayer bonding in asphalt pavements. RILEM State-of-the-Art Reports, Vol. 9, pp. 303-360, Springer, Dordrecht.

Carr, A.G. 2001. The behaviour of layered pavement structures: The dynamic shear box. Project Report NCPE, University of Nottingham, UK.

Carpenter, S., and Shen, S. 2006. A dissipated energy approach to study HMA healing in fatigue. Transportation Research Record (TRR): Journal of the Transportation Research Board, No 1970, pp. 178-185.

Crispino, M., Festa, B., Giannattasio, P., and Nicolosi, V. 1997. Evaluation of the interaction between the asphalt concrete layers by a new dynamic test. Proc., 8th International Conference on Asphalt Pavements, Aug. 10-14, 1997, Seattle, Washington, USA.

Daniel, JS. 1996. Rate dependent stiffness of asphalt concrete used for field to laboratory prediction and fatigue and healing evaluation. M.Sc. Thesis, North Carolina State University, Raleigh.

Deysarkar, I., and Tandon, V. 2005. Field evaluation of tack coat quality measurement equipments. International Journal of Pavement Engineering, Vol. 4(1-2), pp. 25-37.

Di Benedetto, H., Soltani, A., and Shaverot, P. 1996. Fatigue damage of bituminous mixtures. Journal of the Association of Asphalt Paving Technologists. Vol. 65, pp. 142-158.

Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., and Lundström, R. 2004. Fatigue of bituminous mixtures. Journal of Materials and Structures, Vol. 37, pp. 202-216.

Di Benedetto, H., Nguyen, Q-T., and Sauzéat, C. 2011. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 12(1), pp. 129-158.

Di Benedetto, H. 2013. Fatigue and other phenomena during cyclic loading of bituminous materials. Keynote at Int. EATA Conf., Jun. 3-5, 2013, Braunschweig, Germany.

Diakhate, M., Millien, A., Petit, C., Phelipot-Mardele, A., and Pouteau, B. 2011. Experimental investigation of tack coat fatigue performance: Towards an improved lifetime assessment of pavement structure interfaces. Journal of Construction and Building Materials, Vol. 25(2), pp. 1123-1133.

Donovan, E., Al-Qadi, I., and Loulizi, A. 2000. Optimization of tack coat application rate for geocomposite membrane on bridge decks. Transportation Research Record, Journal of the Transportation Research Board, No. 1740, pp. 143-150.

Dowling, N. E. 1999. Mechanical behavior of materials, engineering methods for deformation, fracture, and fatigue. Second Edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

EN 12697-24. 2012. Test methods for hot mix asphalt - Part 24: Resistance to fatigue. European Standard.

EN 1426. 2013. Bitumen and bituminous binders - Determination of needle penetration. European Standard.

EN 13108-20. 2016. Bituminous mixtures - Material specifications - Part 20: Type testing. European Standard.

FGSV, TP Asphalt-StB, Teil 33. 2007. Herstellung von Asphalt-Probeplatten im Laboratorium mit dem Walzsektor-Verdichtungsgerät (WSV). FGSV-Verlag, Forschungsgesellschaft fur Straßen- und Verkehrswesen, Köln.

FGSV. TP Asphalt-StB. Teil 80. 2012. Abscherversuch. FGSV-Verlag, Forschungsgesellschaft fur Straßen- und Verkehrswesen, Köln.

Findley, W.N., Lai, J.S., and Onaran, K. 1976. Creep and relaxation of nonlinear viscoelastic materials. North-Holland Series in Applied Mathematics and Mechanics, Vol. 18, North-Holland Publishing Company, Amsterdam.

Ghosh, Swapan Kumar. 2008. Self-healing materials: fundamentals, design strategies, and applications (1st edition), Wiley-VCH Verlag.

Ghuzlan, K., and Carpenter, S. 2000. An energy-derived, damage-based failure criteria for fatigue testing. Transportation Research Record, Journal of the Transportation Research Board, No. 1723, pp. 141-149.

Ghuzlan K. and Carpenter, S. 2003. Traditional fatigue analysis of asphalt concrete mixtures. Transportation Research Board, Annual meeting (CD-ROM), Paper No. 61801.

Gorszczyk, J., and Malicki, K. 2012. Influence of the tack coat material on interlayer bonding properties in asphalt layers system. Proc., 4th European Pavement and Asset Management Conference, EPAM, Sept. 5-7, 2012, Malmo, Sweden.

Hintz, C. 2012. Understanding mechanisms leading to asphalt binder fatigue. Thesis, University of Wisconsin - Madison, USA.

Hintz, C., and Bahia, H. 2013. Simplification of linear amplitude sweep test and specification parameter. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2370, pp. 10-16, Washington, D.C.

Hopman, P., Kunst, P., and Pronk, A. 1989. A renewed interpretation model for fatigue measurement. Verification of Miner´s rule. Proc., 4th Eurobitumen Symposium, Oct. 4-6, 1989, Madrid.

Huang, Y. 2004. Pavement Analysis and Design. Pearson Prentice Hall, USA.

Hugener, M. 2017. Hot recycling: state of the art and new challenges in Europe. International Forum, Association of Asphalt Paving Technologists Conference (AAPT), Mar. 19-22, 2017, Newport Beach, California, USA.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 a. Energy dissipation in asphalt mixtures observed in different cyclic stress-controlled fatigue tests. Proc., 8th International RILEM SIB symposium, Vol. 11, RILEM Bookseries, pp. 693-709, Oct. 7-9, 2015, Ancona, Italy.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2015 b. Asphalt recovery properties in fatigue test with single rest period. Proc., 6th international conference - bituminous mixtures and pavements, Jun. 10-12, 2015, Thessaloniki, Greece.

Isailović, I., Wistuba, M, and Cannone Falchetto, A. 2016 a. Assessment of healing properties of asphalt mixtures. Proc., 8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements, Vol. 13, RILEM Bookseries, pp. 253-258, Jun. 7-9, 2016, Nantes, France.

Isailović, I., Cannone Falchetto, A., and Wistuba, M. 2016 b. Characterization of asphalt mixture recovery properties based on dissipated energy approach. International Society for Asphalt Pavements Symposium, Jul. 18-22, 2016, Jackson Hole, Wyoming, USA.

Isailović, I., Wistuba, M., and Cannone Falchetto, A. 2017 a. Influence of rest period on asphalt recovery considering nonlinearity and self-heating. Journal of Construction and Building Materials, Vol. 140, pp. 321-327.

Isailović I., Cannone Falchetto A., and Wistuba M. 2017 b. Fatigue investigation on asphalt mixture layers' interface. Journal of Road Materials and Pavement Design, Vol. 18, sup4, pp. 514-534.

Isailović, I., and Wistuba, M. 2017. Veränderungen in den mechanischen Asphalteigenschaften bei verschiedenen spannungsgeregelten Ermüdungsprüfungen. Straße und Autobahn (within review process), Vol. 68, pp.7-12.

Jacobs, M.M.J. 1995. Crack growth in asphalt pavements. Thesis, Delft University of technology, The Netherlands.

Johnson, C. M. 2010. Estimating asphalt binder fatigue resistance using an accelerated test method. Thesis, University of Wisconsin, Civil & Environmental Engineering, Madison, USA.

Jones, A.S., and Dutta, H., 2010. Fatigue life modeling of self-healing polymer systems. Journal of Mechanics of Materials, Vol. 42, pp. 481-490.

Kim, Y.R., Little, D.N., and Lytton, R.L. 2003. Fatigue and healing characterization of asphalt mixtures. Journal of Materials in Civil Engineering, Vol. 15(1), pp. 75-83.

Kim, B., and Roque, R. 2006. Evaluation of healing property of asphalt mixtures. Transportation Research Record, Journal of the Transportation Research Board, No. 1790, pp 84-91.

Kringos, N., Schmets, A., and Scarpas, A. 2011. Towards an understanding of the self-healing capacity of asphaltic mixtures. HERON, Vol. 56 (1/2), pp. 45-47.

Kruntcheva, M.R., Collop, A.C., and Thom, N.H. 2005. Effect of bond condition on flexible pavement performance. Journal of Transportation Engineering, Vol. 131(11), pp. 880-888.

Leutner R. 1979. Untersuchung des Schichtenverbundes beim bituminösen Oberbau. Bitumen, Vol. 3, pp. 84-91.

Little, D.N., Lytton, R.L., Williams, D., and Kim, Y.R. 1999. An analysis of the mechanism of microdamage healing based on the application of micromechanics first principles of fracture and healing. Journal of the Association of Asphalt Paving Technologists, Vol. 68, pp. 501-542.

Little, D.N., Lytton, R.L., Devon, W., and Chen, C.W. 2001. Microdamage healing in asphalt and asphalt concrete, Vol. I: Microdamage and microdamage healing. Project Summary Report. FHWA-RD-98-141, Texas Transportation Institute, The Texas AandM University System, College Station, USA.

Lundström, R., Ekblad, J., and Isacsson, U. 2004. Influence of hysteretic heating on asphalt fatigue characterization. Journal of Testing and Evaluation, Vol. 32 (6), pp. 484-493.

Luo, X. 2012. Characterization of fatigue cracking and healing of asphalt mixtures. Thesis, Texas A&M University, College Station, Texas, USA.

Luo, X., Luo, R., and Lytton, L. 2013. Characterization of recovery properties of asphalt mixtures. Journal of Construction and Building Materials, Vol. 48, pp. 610-621.

Maillard, S., de La Roche, C., Hammoum, F., Such, C., and Piau, J-M. 2004. Bitumen healing investigation using a specific fracture test. Journal of Road Materials and Pavement Design, Special Issue EATA 2004, Vol. 5, pp. 45-63.

Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, F., and Planque, L. 2015. Quantification of biasing effects during fatigue tests on asphalt mixes: non-linearity, self-heating and thixotropy. Journal of Road Materials and Pavement Design, Vol. 16, pp. 73-99.

Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, F. and Planque, L. 2017. Complex modulus and fatigue performances of bituminous mixtures with reclaimed asphalt pavement and a recycling agent of vegetable origin. Journal of Road Materials and Pavement Design, Vol 18. No. 2, pp. 315-330.

Molenaar, A.A.A. 2007. Prediction of fatigue cracking in asphalt pavements: Do we follow the right approach? Transportation Research Record: Journal of the Transportation Research Board, No 2001, pp. 155-162.

Mollenhauer, K., and Wistuba, M. 2009. Fatigue testing of hot mix asphalt - Is there a way to reduce the test effort while getting adequate input for pavement design? Proc., 8th International conference on the bearing capacity of roads, railways, and airfields, June 29 - July 2, 2009, Champaign, Illinois, USA.

Moreno-Navarro, F., Sol-Sanchez, M., Rubio-Gamez, M.C. 2015. Exploring the recovery of fatigue damage in bituminous remixtures: the role of healing. Journal of Road Materials and Pavement Design, Vol. 16, pp. 1-15.

Muench S., and Moomaw T. 2008. Debonding of hot mix asphalt pavements in Washington State: an initial investigation. Technical Report TNW 2008-10, Transportation Northwest (TransNow), University of Washington and Washington State Transportation Commission, USA.

Nazzal, M., Kaya, S., and Abu-Qtaish, L. 2012. Evaluation of WMA healing properties using atomic force microscopy. Proc., 7th RILEM International conference on cracking in pavements, Vol.4, RILEM Bookseries, pp. 1125-1134, Delft, The Netherlands.

NCHRP. 2004. Guide for mechanistic-empirical design of new and rehabilitated pavement structures. Appendix II-1: Calibration of fatigue cracking models for flexible pavements. Illinois, USA.

Pellinen, T. 1998. The assessment of validity of using different shifting equations to construct a master curve of HMA; University of Maryland: College Park, MD, USA.

Pérez-Jiménez, F., Miró, R., and Martínez A.H. 2011. Effect of thermal stresses on fatigue behavior in bituminous mixes. Transportation Research Record, Journal of the Transportation Research Board, No. 2210, pp. 90-96.

Pérez Jiménez, F.E., Botella Nieto, R., Martínez Reguero, A.H., and Miró Recasens, J.R. 2013. Estimating the fatigue law of asphalt mixtures using a strain sweep test (EBADE test). Proc., 5th International EATA Conference, Jun. 3-5, 2013, Braunschweig, Germany.

Perez-Martinez, M., Marsac, P., Gabet, T., Hammoum, F., Mesquita Lopes, M. and Pouget, S. 2016. Effects of ageing on warm mix asphalts with high rates of reclaimed asphalt pavement. Proc., 8th International RILEM Conference on Mechanisms of Cracking and Debonding in Pavements, Vol. 13, Jun. 7-9, 2016, pp. 113-118, Nantes, France.

Palvadi, S., Bhasin, A., Motamed, A., and Little, D.N. 2012. Quantifying healing based on viscoelastic continuum damage theory in fine aggregate asphalt specimen. Proc., 7th RILEM International conference on cracking in pavements, Vol.4, RILEM Bookseries, pp. 1115-1123, Delft, The Netherlands.

Phillips, MC. 1998. Multi-step models for fatigue and healing, and binder properties involved in healing. Eurobitume workshop on performance related properties for bituminous, May 3-6, 1998, Luxembourg, No. 115.

Qiu, J., 2012. Self healing of asphalt mixtures towards a better understanding of the mechanism. Thesis, Delft University of Technology, The Netherlands.

Raab, C., and Partl, M. 2004. Interlayer shear performance: Experience with different pavement structures. Proc., 3rd Eurasphalt and Eurobitumen Congress, May 12-14, 2004, Vienna.

Rabe, R. 2008. From loads to roads - the way from truck freight to pavement stress. Proc., Transport Research Area Europe, Apr. 21-24, 2008, Ljubljana, Slovenia.

Renken, P. 2000. Influence of specimen preparation onto the mechanical behaviour of asphalt aggregate mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, pp. 729-735, Sept. 20-22, 2000, Barcelona, Spain.

Romanoschi, S.A., and Metcalf, J.B. 2001. The characterization of asphalt concrete layer interfaces. Transportation Research Record, Journal of the Transportation Research Board, No. 1778, pp. 132-139.

Romanoschi, S.A., and Metcalf, J.B. 2002. The characterization of pavement layer interfaces. Proc., 9th International Conference on Asphalt Pavements, August, 17-22, 2002, Copenhagen, Denmark.

Rowe, G.M., and Bouldin, M. G. 2000. Improved techniques to evaluate the fatigue resistance of asphaltic mixtures. Proc., 2nd Eurasphalt and Eurobitume Congress, Sept. 20-22, 2000, Barcelona, Spain.

Sanders, P.J. 2001. Reinforces asphalt overlays for pavements. Thesis, University of Nottingham, UK.

Santagata, E., and Canestrari, F. 1994. Tensile and shear tests of interfaces in asphalt mixes: A new prospective on their failure criteria. Proc., 2nd International Symposium, Ulster, Northern Ireland.

Santagata, E., Baglieri, O., Dalmazzo, D., and Tsantilis, L. 2009. Rheological and chemical investigation on the damage and healing properties of bituminous binders. Association of Asphalt Paving Technologists, Vol. 78, pp. 567-596.

Santagata, E., Baglieri, O., Tsantilis, L., and Dalmazzo, D. 2013. Evaluation of self healing properties of bituminous binders taking into account steric hardening effects. Journal of Construction and Building Materials, Vol. 41, pp. 60-67.

Sefidmazgi, N.R., Tashman, L., and Bahia, H. 2012. Internal structure characterization of asphlat mixtures for rutting performance using imaging analyses. Journal of Road Materials and Pavement Design, Vol. 13(S1), pp. 21-37.

Shan, L., Tan, Y., and Kim, R. 2013. Establishment of a universal healing evaluation index for asphalt binder. Journal of Construction and Building Materials, Vol. 48, pp. 74-79.

Shen, S., and Carpenter, S. 2007. Dissipated energy concepts for HMA performance: fatigue and healing. Technical report supported by Federal Aviation Administration, University of Illinois, USA.

Shen, S., Chiu, H., and Huang, H. 2009. Fatigue and healing in asphalt binders. CD-ROM. Transportation Research Board Meeting, Washington, D.C.

Sholar, G. A., Page, G. C., Musselman, J. A., Upshaw, P. B., and Moseley, H. L. 2004. Preliminary investigation of a test method to evaluate bond strength of bituminous tack coats. Journal of the Association of Asphalt Paving Technologists, Vol. 73, pp. 771-806.

Soltani, A., and Anderson, D.A. 2005. New test protocol to measure fatigue damage in asphalt mixtures. Journal of Road Materials and Pavement Design, Vol. 6(4), pp. 485-514.

Sonmez, I., Ali Yildirim, S., and Temren, Z. 2016. Investigation of performance properties of laboratory and plant produced bituminous mixture containing high rates of reclaimed asphalt. Proc., 6th Eurasphalt & Eurobitume Congress, Jun. 1-3, 2016, Prague.

Spencer, A.J.M. 1980. Continuum Mechanics (Dover Books on Physics), Dover, New York, USA.

Stephens, R.I., Fatemi, A., Stephens, R.R, and Fuchs, H. O. 2001. Metal Fatigue in Engineering (2nd edition). A Willey-Interscience Publication, John Wiley & Sons, INC.

Sutanto M.H. 2009. Assessment of bond between asphalt layers. Thesis, University of Nottingham, UK.

Tan, Y., Shan, L., Kim, Y., and Underwood, B.S. 2012. Healing characteristics of asphalt binder. Journal of Construction and Building Materials, Vol. 27, pp. 570-577.

Tozzo, C., D'Andrea, A., Cozzani, D., and Meo, A. 2014. Fatigue investigation of the interface shear performance in asphalt pavement. Journal of Modern Applied Science, Vol. 8(2), pp. 1-12.

Tschegg, E.K., Kroyer, G., Tang, D., Stanzl-Tschegg, S.E., Litzka, J. 1995. Investigation of bonding between asphalt layers on road construction. Journal of Transportation Engineering, Vol. 121(4), pp. 309-317.

Underwood, B., Baek, C., and Kim, Y. 2012. Simplified viscoelastic continuum damage model as platform for asphalt concrete fatigue analysis. Transportation Research Record: Journal of the Transportation Research Board, No 2296, pp. 36-45.

Van den Bergh, W. 2011. The effect of ageing on the fatigue and healing properties of bituminous mortars. Thesis, Delft University of Technology, The Netherlands.

Van den Bergh, W., and Van der Ven M.F.C. 2012. The influence of ageing on the fatigue and healing properties of bituminous mortars. Proc., SIIIV-5th international congress-sustainability of road infrastructures, Oct. 29-31, 2012, Rome.

Weber, R. 1991. Die Rißbildung in Asphaltstraßen als Folge mangelhaften Schichtenverbundes (Dissertation). Prüfamt fur Bau von Landverkehrswegen, Technische Universitat München, Germany.

Wellner, F., and Ascher, D. 2007. Untersuchung zur Wirksamkeit des Haftverbundes und dessen Auswirkung auf die Lebensdauer von Asphaltbefestigungen (Schlussbericht, AiF Forschungsvorhaben Nr. 13589 BR/1). Professur fur Straßenwesen, Technische Universität Dresden.

Wellner F., and Hristov, B. 2016. The effect of interlayer bond on the service life of asphalt pavements. Proc., 4th Annual International Conference on Architecture and Civil Engineering, Global Science and Technology Forum (GSTF), Apr. 25-26, 2016, Singapore, pp. 444-449.

West, R. C., Zhang, J., and Moore, J. 2005. Evaluation of bond strength between pavement layers (NCAT Report 05-08). National Center for Asphalt Technology, University of North Carolina, USA.

Wheat, M. 2007. Evaluation of bond strength at asphalt interfaces. Master thesis, Kansas State University, USA.

Wistuba, M., and Perret, J. 2004. Comparative strain measurement in bituminous layers with the use of ALT. Proc., 2nd international conference on accelerated pavement testing, Sept. 25-29, 2004, Minneapolis, USA.

Wistuba, M., Monismith, C., Bahia, H.U., Renken, P., Olard, F., Blab, R., Mollenhauer, K., Metzker, K., Büchler, S., Grönniger, J., Zeng, M., and Nam, K. 2009. Asphalt material behaviour at low temperatures. Essays in honour of Professor Wolfgang Arand on the occasion of his 80th birthday. Schriftenreihe Straßenwesen, Heft Nr. 23, Braunschweig Pavement Engineering Centre, Technische Universität Braunschweig.

Wistuba, M., Alisov, A., and Isailović, I. 2013. Ansprache und Steuerung von Healing-Effekten bei Asphalt. Schlussbericht, FE 07.0251/2011/ERB, i. A. des Bundesministeriums für Verkehr, Bau und Stadtentwicklung, Institut für Straßenwesen, Technische Universität Braunschweig.

Wistuba, M. 2014. The German segmented steel roller compaction method - state-of-the-art report. International Journal of Pavement Engineering Vol. 17, pp. 81-86.

Wistuba, M. P., Grönniger, J., and Isailović, I. 2015. Optimierung des Recyclinganteils in Asphalttrag- und -binderschichten (ORAB). Forschungsprojekt F&E-Projekt ORAB i.A. Schlussbericht, Bundesministerium für Verkehr, Innovation und Technologie ÖBB-Infrastruktur AG Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft, Bundesministerium für Verkehr, Innovation und Technologie, Abteilung Mobilitäts- und Verkehrstechnologien, Wien.

Wistuba, M., Isailović, I., and Büchler, S. 2016. Zyklische Schersteifigkeits- und Scherermüdungsprüfung zur Bewertung und Optimierung des Schichtenverbundes in Straßenbefestigungen aus Asphalt (Schlussbericht Nr. 17634 BG/2. i. A. der AIF). Institut für Straßenwesen, Technische Universität Braunschweig.

Woods, M. E. 2004. Laboratory evaluation of tensile and shear strengths of asphalt tack coats. Master thesis, Mississippi State University, Starkville, USA.

Wool, R.P. 2008. Self-healing materials: a review. Journal of Soft Matter 4, pp. 400-418.

Zofka, A., Maliszewski, M., Bernier, A., Josen, R., Vaitkus, A., and Kleiziene, R. 2015. Advanced shear tester for evaluation of asphalt concrete under constant normal stiffness conditions. Journal of Road Materials and Pavement Design, Vol. 16, pp. 187-210.

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